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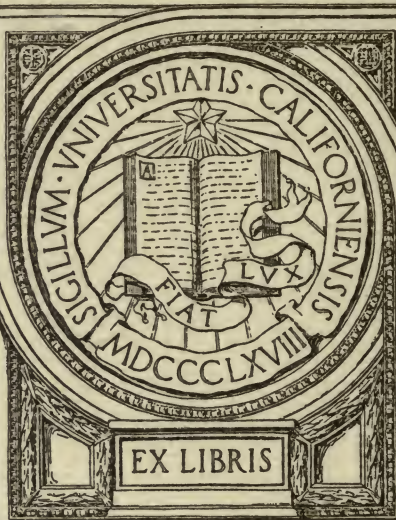
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NEW
LABORATORY MANUAL
OF PHYSICS

S. E. COLEMAN

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NEW LABORATORY MANUAL OF PHYSICS

BY

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W. P. 7

PREFACE

THAT laboratory work is an important part of a course in elementary physics is no longer open to question. The opinion is also practically unanimous that the laboratory work should constitute an organic and integral part of the course, pursued concurrently with the instruction of the class room throughout the subject. Beyond this point, however, there is still a considerable diversity of opinion and practice within the limits of good teaching. While the author believes that this Manual will be found adapted to any approved plan of work, it will not be out of place to present the point of view from which the book was written.

Its scope is that of a laboratory guide for the pupil. It encroaches as little as possible on the province of the text-book, and does not include class-room experiments to be performed by the teacher. Many such experiments must be presented in any well-conducted course in physics; but it is unnecessary to place the directions for them in the hands of the pupils.

Every experiment in the course is a *physical* experiment. With a superabundance of excellent material within the scope of elementary physics, there would seem to be no valid reason for spending the first days in the laboratory on manipulation and measurement with vernier and micrometer calipers, the diagonal scale, the spherometer, etc., as is sometimes done, with no physics in sight.

The course aims to present a maximum of physics with a minimum of manipulation. So far as the teaching of elementary science is concerned, skill in manipulation must be regarded as a means to an end, not as an end in itself. The more simply

and directly a physical problem is presented to the pupil the better, that his thought and attention may not be diverted from the real point at issue. This principle is especially applicable in the early part of the laboratory course, where it is most frequently and most seriously violated by the use of micrometric instruments, the Jolly balance, etc., in the work on density and specific gravity, even before the pupil has had practice in the simpler methods of measuring and weighing. It would seem as if the express purpose of such work were at the outset to throw as many obstacles in the way of progress in physics as the ingenuity of teachers and instrument makers could devise.

To be entitled to a place, a laboratory experiment must serve a definite purpose in the general plan of the course; it must contribute something of value in the unfolding of that plan. Perhaps the most striking illustration of what should not be done in this respect is afforded by the familiar quantitative experiments on the breaking strength of wires and on elasticity of stretching, bending, and twisting. These experiments lead absolutely to nothing in most high-school courses. The laws with which they deal are, for the most part, not considered in elementary text-books. A simple qualitative treatment in the class room or the laboratory would serve as an ample experimental basis for all the applications that are or need be considered in a general high-school course.

The qualitative experimental study of phenomena rightly demands a large place in an elementary physics course. Economy of time and equipment, convenience, and the advantage of the superior skill of the teacher, are considerations in favor of presenting much of this material in the form of class-room experiments; but in a great many instances the laboratory experiment, affording, as it does, immediate sense perception of the phenomena in their simplest aspects and at close range, is greatly superior to any experiment viewed at a distance; and a laboratory course which fails to take this into account is necessarily one-sided and incomplete. No apology is therefore necessary

for the large number of qualitative experiments in this Manual. They are entitled to consideration. To lessen the burden of the laboratory record, which rests rather heavily on teacher and pupil alike, it is suggested that many of the qualitative experiments may be made nearly, if not quite, as valuable a part of the laboratory course without requiring a written record of them. In such cases the discussion of the observed phenomena in the recitation will suffice.

Physics should be so taught that the pupil will be led to a correct view of the significance of his laboratory work in its relation to the subject as a science. He should understand that the validity of scientific generalizations, particularly those of a quantitative character, does not depend upon the necessarily inaccurate and incomplete data gathered from the experiments of the class room and the laboratory. These experiments should be regarded as a limited inquiry into the facts at first hand, not as sources of adequate data for generalizations by the pupil, nor as "verifications" of the laws and principles stated in the text. The pupil's experiment is not a proof of the law, but an aid to the right understanding of it. For example, under Boyle's law the pupil performs an experiment with one gas only (air), at one temperature only, and with only a moderate range of pressure. With the apparatus ordinarily provided, the work is well done if it is not in error by more than two per cent. It would be no less than a complete perversion of the distinctive aims and purposes of scientific instruction to lead the pupil to regard such an experiment as a verification or proof of Boyle's law; namely, that the inverse proportionality of volume and pressure is true (*accurately true*) for all gases at any temperature and under all ranges of pressure. It is hardly necessary to say that Boyle's law is not verified until the experiment is repeated at many different temperatures with every gas, and performed with an accuracy equal to that of the ablest experimenters. It would then be found (as the texts state) that the usual statement of the law is not exact, and that it wholly fails for any gas

when near a temperature and pressure at which it liquefies. Since the pupil does not undertake such an investigation, he neither proves nor disproves the law. What he really does is to perform an experiment which, within a fair degree of accuracy, illustrates or exemplifies the law; and he does this in order that he may the better understand it, not because the law is in need of "verification."

It is of course true that the laboratory work affords a sufficient basis for important inferences and conclusions; but these are necessarily simple, and generally narrow and partial. They must be limited to what follows legitimately from the experimental data. To encourage the pupil to draw hasty and unwarranted conclusions from insufficient data is a vicious practice.

This point of view concerning the function of experimental work in elementary physics is maintained throughout the Manual, particularly in the statement of the purpose of each experiment and in the questions asked in the discussions. Consistently with the view that the laboratory course is not a sufficient basis from which to evolve physics as a science, it is assumed in the discussion of experimental results that the pupil has at least carefully read his text-book on the subject of the experiment, and is therefore in a position not only to state the conclusions which are supported by his work, but also to pass judgment on the quality of it by comparing his results with those known to be correct.

To provide opportunity for choice and to increase the adaptability of the Manual to the varying equipment of different laboratories, the number of exercises has been made considerably greater than most teachers will require in a one-year course. A course of sixty exercises, properly distributed over the different parts of the subject, would constitute a liberal provision of laboratory work, and fifty exercises a reasonable minimum. The following exercises are suggested as, on the whole, the best adapted to such a minimum course, having regard to the cost of equipment and also to the fact that many of the experiments,

or others serving the same purpose, can be performed by the teacher before the class, with satisfactory results: Exercises 1-5, 6 (any two of the four experiments), 7, 9, 10, 11 or 12, 13, 14, 16 or 17, 19 or 21, 20, 23-25, 26 (Exp. 50), 29-34, 36, any two of 37 to 41, 42, 43, 45, 47-52, 54 or 55, 56, 57-63, 64 (either experiment), 66 (any one of the experiments), 70, 73.

The experiments have been chosen and planned with due regard to a reasonable economy in the equipment of the laboratory and a moderate degree of accuracy in quantitative results. It is far better to have from two to six sets of apparatus of medium cost for each experiment, so that the entire class can be accommodated without running more than from two to four exercises simultaneously, than to provide only one set of expensive apparatus for each experiment. On the other hand, it is not a wise economy to spend money on cheap apparatus, lacking in durability and efficiency. The instruments shown in the cuts throughout the book are recommended as of satisfactory grade.

The grouping of related experiments into exercises will commend itself as a convenience both to teacher and pupil. It is intended that, in the regular progress of the work, one laboratory period (either single or double) will be devoted to each exercise. The whole of a single laboratory period will ordinarily be required for the experimental work of the exercise, with only a preliminary record of it in the form of rough notes; and time outside the laboratory must be taken for writing the permanent record. A double laboratory period (an hour and a half) should be sufficient for both the experimental work and the final record.

While the present work is in greater part a revision of the author's "Physical Laboratory Manual," it is newly written throughout; and full advantage has been taken of the opportunity to make the many improvements in subject-matter, arrangement, and presentation which have been made possible by later years of experience.

S. E. COLEMAN.

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Special catalogues of the apparatus for this manual are issued by the University Apparatus Co., 2229 McGee Ave., Berkeley, California; and by the Chicago Apparatus Co., 557-559 W. Quincy St., Chicago, Illinois.

NEW LABORATORY MANUAL OF PHYSICS

I. GENERAL DIRECTIONS

1. The following general directions should be carefully studied before the laboratory work is begun. It is not to be expected that they will all be fully understood until, by actual experience in the laboratory, the pupil has become somewhat acquainted with the various matters with which they deal. It will therefore be necessary to refer to them frequently during the first few weeks, until they become thoroughly familiar.

THE LABORATORY WORK

2. **Preparation.** — Finish the record of each laboratory exercise before beginning the next. It is generally impossible to perform an experiment intelligently unless the lessons to be drawn from the experiments immediately preceding have been definitely learned.

If the subject with which the exercise deals is not already familiar from previous class-room work, read the text-book on the subject before the laboratory period. Read also the laboratory directions for the exercise. The preliminary information thus gained lessens the danger of misdirected effort in the laboratory and makes the work much easier to understand.

The references indicated at the beginning of each exercise may be consulted during the laboratory period, as opportunity offers, or at such other times as the instructor may direct.

To save time in the laboratory, tabular forms for the record of measurements should be prepared in advance.

3. **Apparatus.** — Before beginning an exercise note whether you have everything called for in the list of apparatus. If any-

thing is missing or unsatisfactory, report the fact to the instructor at once. *Never* take apparatus from other places than your own.

4. Neatness and Order.—A very important incidental benefit of a properly conducted laboratory course is the training it affords in neatness and order. Pupils should feel a personal responsibility for the condition of the apparatus and table where they are at work, and especially for the condition in which these are left at the end of the hour. A proper regard for the comfort and convenience of others demands that you leave the place you have occupied at least as clean and orderly as you found it.

5. Damage to Apparatus.—Pupils are responsible for all damage to apparatus in their possession, and should report such damage to the instructor immediately.

6. Economy of Time in the Laboratory.—It is expected that each exercise will be completed in one laboratory period. To make sure of accomplishing this, no time should be taken in the laboratory for writing discussions or for making computations (unless the results of these computations are needed at the time), until the exercise for the day is completed. The remainder of the period may be spent either in reading the references or in writing up the exercise. No time should be wasted.

7. Questions.—Numerous questions are interspersed with the directions for the experimental work. Do not pass over these questions, leaving them for later consideration. They direct the attention to matters that should be understood at the time—with the assistance of the teacher, if necessary. The answers to questions in parentheses may be omitted from the record.

8. Repetition of Work.—An experiment is to be repeated when the results are unsatisfactory. Present doubtful results to the teacher for his decision as soon as possible, so that the experiment may be repeated, if necessary, without delay.

THE LABORATORY RECORD

9. Specific Directions concerning the manner of taking notes during the progress of experimental work and the form and scope of the final record will be given by the teacher. In addition to these, the following general directions should be carefully observed.

10. General Form.—Copy the number and title of each exercise and the purpose of each experiment (printed in italics) from the manual ; and arrange the notes on each experiment under the various heads there indicated. Give proper attention to regularity of margins, paragraphing, spacing, numbering, lettering, etc. Do not crowd the notes. Leave a vacant line between the experiments of an exercise, and several vacant lines between exercises. Make headings prominent. In all these matters of general form the record should correspond with the manual.

Measurements, computations, and numerical results should always be set apart by themselves, so as to be easily seen and compared. Sets of numbers are best entered in columns, as in Exercises 1, 8, 11, 12, etc. Single items should be given one or more whole lines each, with the numbers at the right-hand side of the page, as in Exercises 1, 2, 4, 5, etc. When no form of record is given for an experiment, devise a satisfactory one for yourself.

11. Clearness and Brevity.—The record should be complete in itself, *i.e.* should not require a knowledge of the directions or the questions asked in the manual to make it fully intelligible. It should be as brief as possible without sacrificing clearness or omitting essentials. The answers to questions *inclosed in parentheses* may be omitted from the record ; but these questions should receive no less careful attention on that account. Be prepared to answer them orally at any time.

12. Decimals.—Express all fractional quantities decimally. The relative values of fractions expressed decimally can be determined at a glance, but in the form of common fractions this is generally impossible. In the actual work of measuring and com-

puting, the decimal fraction is almost without exception more convenient than the common fraction. This is especially true in using the metric system.

Express a quantity in terms of one unit only ; *e.g.* write 15.25 g. instead of 15 g. 2 dg. 5 cg. Express all lengths in centimeters.

13. What constitutes an Honest Record.—Your laboratory notes are accepted upon the supposition that they are a true record of the work done by *you* in the laboratory. If the results are not satisfactory, *the only remedy is to repeat the experiment.* Neither borrowing nor lending of note books can be permitted. Where pupils work in pairs each should always take a complete record of all measurements and other necessary data, so as to be wholly independent of his laboratory mate in writing up the exercise, and each should perform all computations for himself. Pupils may, of course, give one another the kind of help that they might expect from the teacher.

COMPUTATIONS

14. The Record of Computations.—The mathematical processes by which computed results are obtained must either be fully recorded or indicated by means of the signs of addition, subtraction, etc. In the first two exercises the computations are indicated in the model form of record, parentheses being used to represent the numbers. You are expected to remember this direction and to observe it in all subsequent work without such a reminder.

Where results are entered in tabular form, and the computations indicated at the tops of the columns, only the results are to be entered in the columns.

15. Concrete Numbers.—The name of the unit should always be written after the numerical value of a measured or computed quantity. This applies to each quantity recorded in a series of computations as well as to the final result. Failure to keep track of the physical units involved in computations is a fruitful source

of errors in the solution of problems as well as in the laboratory work.

➤ **16. Testing Numerical Results.** — When an experiment leads to a numerical result the true value of which is known, — as the weight of a cubic centimeter of pure cold water (Experiment 3), — a comparison of the experimental value with the true value of the quantity serves as a check on the work, to determine whether it has been done with reasonable care and accuracy. The method of making such a comparison is illustrated by the following example.

If a length of 10.05 cm. is measured and recorded as 10 cm., the error is .05. This is $.05 \div 10.05$, or .005, of the quantity measured, or .5% of it. An equal error (.05 cm.) in measuring a length of 2.5 cm. is 2% of the quantity measured. In the second case the error is of more consequence because it is a larger fraction of the quantity measured. To illustrate further, if an error of only an inch were made in measuring off a mile, the work would be considered very accurate; but the measured height of a table would be very inaccurate if it were in error by as much as an inch. It will be seen that the degree of accuracy of a measurement is not expressed by the error, but by *the percentage of error*.

If the percentage of error of any result is unreasonably large, the experiment should be repeated as soon as possible. Only reasonably accurate results should be handed in for inspection.

17. How the Accuracy of Measurements enters into Computations. — To retain either more or fewer decimal places in a computed result than the accuracy of the measurements justifies is an error to be carefully avoided. The principles and rules governing correct practice in this matter are illustrated in the following examples.

In the first laboratory exercise it is required to determine the volume of a rectangular solid. The length is measured near each of the four edges extending in that direction, and the values

found are, let us say, 7.25 cm., 7.23 cm., 7.24 cm., and 7.23 cm. The average of these numbers is 7.2375 cm. Now the last figure in each of the four measurements is doubtful, the estimate of hundredths of a centimeter (or tenths of a millimeter) being uncertain by at least one or two hundredths; hence the 3 in the second decimal place of the average is doubtful, and the last two figures should be dropped. But since the first figure discarded is greater than 5, the last figure retained is increased by one; *i.e.* the average is written 7.24 cm. To retain the four decimal places would be wrong, since this would imply a greater accuracy than was actually attained in the measurements. It would also be wrong to drop all but the first decimal figure, since we have good reason for thinking that 7.24 cm. is more nearly right than 7.2 cm.

Let us suppose further that the average width of the solid is found to be 5.78 cm., and the average thickness 3.18 cm.

The volume of the body = $7.24 \times 5.78 \times 3.18$ c.c.

7.24	41.8
<u>5.78</u>	<u>3.18</u>
5792	3 344
5 068	4 18
36 20	125 4
<u>41.8472</u>	<u>132.924</u>

In the above work the doubtful figures are printed in heavy-faced type. Thus, in the first multiplication, since the last figure, 8, of the multiplier is in doubt, all that depends upon it is in doubt, *i.e.* the entire product, .5792. The volume of the body should be written 133 c.c.

It is easy to see from this example why unreliable figures accumulate in multiplication; but in seeking a practical rule by which to determine what figures should be retained, we must study the question from a different point of view. Suppose in the above example that each dimension of the block is in doubt by .02 cm. This uncertainty, or possible error, is about $\frac{2}{700}$ of the length, $\frac{2}{600}$ of the width, and $\frac{2}{300}$ of the thickness. *The possible error of the product*

is the sum of the possible errors of all the factors, i.e. $\frac{2}{700} + \frac{2}{800} + \frac{2}{900}$, or $\frac{9}{700}$, or (roughly) a little more than 1%. This clearly renders the units' figure of the computed volume doubtful. If we suppose each dimension of the block to be in doubt by only .01 cm., the product will be in doubt by about $\frac{2}{3}\%$; and, as this also makes the units' figure of the product doubtful, the result should still be written 133 c.c. We should, however, be justified in retaining the first decimal place in the computed volume if we had reason to believe that the probable error of each factor was less than .01 cm.

The following table shows how the computed values given in the first column should be written when the probable error is less than 1%, when it is between 1% and 2%, and when it is over 2%.

COMPUTED VALUE	ERROR UNDER 1%	ERROR OF 1% TO 2%	ERROR OVER 2%
214.27	214.3	214.	214
93.628	93.6	93.6	94
10.354	10.35	10.35	10.4
.09567	.0957	.096	.096

As a general rule, computations should be carried to the first doubtful figure, and all decimal places beyond this should be discarded; but in some cases the first two doubtful figures should be retained. For example, if the true value of a quantity is 1.19 and the pupil's value is 1.2263, his answer should be written 1.23, not 1.2; for although the first decimal figure is in error, the omission of the next figure would change the value of the result by 2.5%, which is nearly as great as the experimental error. The omission of the .03 would therefore mask the true quality of the experimental work.

> In division the possible percentage of error of the quotient is the sum of the possible percentage of error of the divisor and dividend, and the same rule holds for retaining decimal places as in multiplication. The division should always be carried far enough to determine whether the first discarded decimal figure is greater or

less than 5. If it is 5 or greater, the last figure retained is increased by one, as in the above examples.

When a result depends upon a series of computations, each computation must be carried far enough to avoid introducing any appreciable error into the work. The safest plan for the beginner is to carry decimal places in excess throughout the computations, and to discard them only in the final result.

18. Detecting Errors of Computation.—Decimal points are frequently misplaced. A mere glance at the numbers is generally sufficient to detect such an error. Thus, if 38.2 be divided by .094, it will be evident at once that the quotient is slightly greater than ten times the dividend (since the divisor is slightly less than .1), and that, if the quotient is written 40.64 or 4064., the decimal point is misplaced.

Misplaced decimal points and other gross errors of computation can often be detected by the absurdity of the results. Thus if one should get .412 g. as the weight of 1 c.c. of a stone in Experiment 2, he should know at once that a serious blunder had been made either in the experimental work or in the computation; for this is less than half the weight of 1 c.c. of water (1 g.), and the pupil knows that, for equal bulk, stone is much heavier than water.

The capable student will soon realize that, in such matters as these, the laboratory work furnishes large opportunity for the exercise and development of all-round "common sense."

19. Mathematical Forms.—The use of inadmissible mathematical forms should be carefully avoided. Perhaps the most common error of this sort is illustrated in the supposed equation:—

$$5 \times 8 \times 10 = 400 \div 500 = .8.$$

This asserts that $400 \div 500 = .8$, which is true; also that $5 \times 8 \times 10 = 400 \div 500$, or $.8$, which is absurd. It is evident, of course, that this is not the meaning intended; but no other interpretation can be given the supposed equation in accordance with established mathematical usage, and no departure from this usage can be tolerated.

MEASUREMENTS

20. Measurement of Length.—The customary unit of length in scientific work is the centimeter; and all lengths are to be recorded in this unit unless otherwise specified. Millimeters are recorded as tenths of a centimeter.

Fractions of a millimeter are estimated in tenths and recorded as hundredths of a centimeter. Thus the length of the block illustrated in Figure 1 is 2.35 cm. The figure also shows the correct position of a meter rod in measuring. If the rod were turned flat, the scale would be

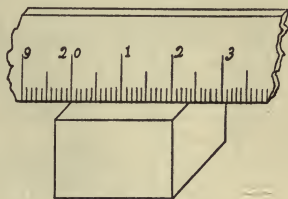


FIG. 1.

at a distance and the measurement would be less accurate. It is best not to use the end of the rod, especially if it is worn. Begin at some even centimeter or, better still, even decimeter.

21. Order of trying Weights in Weighing.—Without system in the use of weights much time is wasted in the process of weighing. A full set of weights, such as is always provided in the laboratory, includes all that are necessary to balance *any* mass from one equal to the sum of all the weights of the set down to one as light as the smallest of the set. But a single set is adequate only when the weights are tried in proper order.

Begin by trying the weight which you estimate to be most nearly equal to the mass to be balanced. If it seems to be nearly sufficient, add the next smaller; but if it is evidently much too light, remove it and try the next larger. Proceed thus backward, trying the larger weights till you find that the next larger, used alone, is too large. *The secret of rapid weighing is to try out the larger weights first.* If the process is begun with too small a weight, this is commonly not discovered till *all* the smaller weights have been added, when the whole process must be repeated, whereas it would have been discovered by trying the single larger weight.

Having thus determined the largest weight to be used, add the smaller weights *in succession*. If any weight proves to be too great an addition, remove *it* (not a larger one) and try the next smaller. Continue thus till you come to the smallest weight provided.

22. Use of the Platform Balance. — The platform balance (Fig. 2) is provided with a graduated beam, which is to be used instead

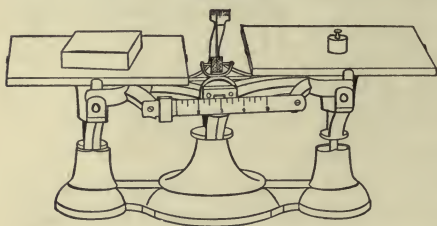


FIG. 2.

of weights smaller than the maximum reading of the beam (usually 5 g.). The platforms are evenly balanced (with nothing on them) when the weight that slides on the beam is at the zero end of the beam. As

the weight is moved from this position, it makes the side toward which it is moved heavier, and the platform on that side descends. The object to be weighed must therefore be placed on the other platform, *i.e.* the one at the zero end of the beam.

In weighing proceed as follows: Place the article to be weighed on the proper platform. Slide the weight on the beam to the zero end. The beam adjustment is to be held in reserve till the weighing has been brought within the limit of the beam reading. When this has been accomplished, make the final adjustment with the beam. You can save time by steadying the platforms with the hands. Do not waste time waiting for the oscillations to cease entirely. Some platform balances are provided with a vertical pointer between the platforms. If the oscillations are small and this pointer moves to approximately equal distances on both sides of the zero point of the graduated arc behind it, the weighing is sufficiently exact. The weight of the object is the sum of the weights used plus the beam reading. This balance is hardly sensitive to less than .1 g., and readings to this fraction are sufficient.

23. Use of the Specific Gravity or Beam Balance.—The beam of this balance (Fig. 3) is not fastened to the upright, and is easily thrown out of place in putting heavy objects on or removing them from the pans. To avoid this, always support the pan on the heavier side by placing a hand under it. When balance is nearly secured, time can be saved by steadying the pans with the hands. Watch the vertical pointer carried by the beam, and adjust the weights according to its indication. The weighing is sufficiently exact when the distances to which the pointer swings on each side of the zero differ by less than one division of the scale behind it. With this balance weight can be determined to the nearest centigram.



FIG. 3.

24. Precautions to be observed in Weighing.—(1) Weights, especially heavy ones, should be placed near the center of the platform or pan.

(2) It is better to handle weights with forceps than with the fingers. If forceps are provided, use them. You will find them more convenient than the fingers, especially in handling the fractional weights.

(3) *Always return weights to the proper places in the block as soon as you have finished weighing.* The most convenient method of counting weights is to add them up *as they are returned to the block*, beginning with the largest and taking them in the order of their size. The weights should never be put down anywhere except on the balance and in their proper places in the block. If one of the weights is lost, the whole set is practically useless.

(4) When fractional weights are provided, they should consist of the following: .5, .2, .1, .1, .05, .02, .02, and .01 g. If any are missing, report the fact to the instructor.

(5) Before using a balance observe whether the beam swings freely and comes to rest in a horizontal position. If it does not, a bearing is probably out of adjustment.

(6) In weighing liquids, see that the outside of the vessel is dry before placing it on the balance. If any liquid is spilled, wipe it up at once.

25. The Estimation of Tenths. — All laboratory measurements should be as accurate as is possible with the apparatus provided. In reading a scale of any sort, — as the position of a point on a meter rod, the position of the pointer on the scale of a spring balance, the height of the mercury in a thermometer, etc., — *the scale should be read to tenths of its smallest division.* Even if the pupil has not the skill to do this accurately, the estimate will be considerably more accurate than the nearest whole division; and it is the universal rule that no error should be unnecessarily introduced into the work.

26. Text-book References. — The text-books referred to by paragraph numbers at the beginning of each exercise are named below. The references are limited to the subject-matter of the experiments, their purpose being to indicate the reading that may profitably precede and accompany the laboratory work, without entering upon the equally wide range of topics which fall within the scope of the recitation.

Adams. Physics for Secondary Schools. Adams.

American Book Company.

Coleman. Elements of Physics. Coleman.

D. C. Heath and Company.

Car. & C. High School Physics. Carhart and Chute.

(Edition of 1907.) Allyn and Bacon.

Ches. G. & T. Physics. Cheston, Gibson and Timmerman.

D. C. Heath and Company.

Hoad. Br. A Brief Course in Physics. Hoadley.

American Book Company.

- Hoad. El. Elements of Physics. Hoadley.
American Book Company.
- Mumper. A Text-book in Physics. Mumper.
American Book Company.
- Mil. & G. First Course in Physics. Millikan and Gale.
Ginn and Company.
- Went. & H. A Text-book of Physics, Revised.
Wentworth and Hill. Ginn and Company.
- Jackson. Elementary Electricity and Magnetism.
Jackson and Jackson. Macmillan Company.

II. DENSITY

EXERCISE I. DENSITY OF SOLIDS

References.—Adams, 1-16; Coleman, 13-20; Car. & C., 7-10, 140; Ches. G. & T., 4-8, 15-17, 19-20; Hoad. Br., 13-15, 145; Hoad. El., 12-16, 156; Mumper, 7-9, 16-18; Mil. & G., 12-18; Went. & H., 11-15.

Experiment 1.—*To find the mass of one cubic centimeter of a rectangular solid.*¹

Apparatus.—A rectangular solid, several centimeters in each dimension; platform balance and weights; forceps for handling weights; metric rule (preferably a 30-cm. rule with beveled edge).

Experimental Work.—Find the dimensions of the solid in centimeters and its weight in grams. Since the solid may not be perfectly rectangular (and very probably is not), four measurements of each dimension are to be taken, one near each of the four edges extending in the direction of the length, and similarly for the width and thickness. Record the four measurements of each dimension even if they are all equal. (Why?) In weighing the solid be sure to place it on the proper platform.

Data and Computations.—Compute the volume of the body from its average length, width, and thickness; then compute its density. Record measurements and computations as follows:—

DIMENSIONS OF THE SOLID

LENGTH		WIDTH	THICKNESS
— cm.		— cm.	— cm.
— cm.		— cm.	— cm.
— cm.		— cm.	— cm.
— cm.		— cm.	— cm.
Av. — cm.		— cm.	— cm.

¹ Use the name of the substance instead of the word "solid."

Weight of the solid = — g.
 Volume of the solid = () $\times$ () $\times$ () = — c.c.
 Density of the solid = () $\div$ () = — g. per c.c.

Experiment 2.—*To find the density of an irregular solid that sinks in water.*

Apparatus.—Platform balance and weights; overflow can (Fig. 4); tumbler; vessel of water; cubic centimeter graduate; irregular solid¹ with string tied to it; mop cloth.

[The copper boiler used in several of the heat experiments serves very well for an overflow can, if a short piece of rubber tubing is attached to the spout. A cubic centimeter graduate having a capacity of 100 c.c. and graduated in single cubic centimeters is recommended as most serviceable for laboratory work.]

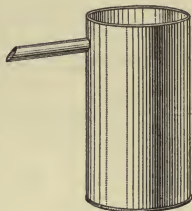


FIG. 4.

Experimental Work.—Weigh the solid before putting it in water; then find its volume by measuring the volume of water that it displaces when immersed. If the spout of the overflow can is not high enough to allow the graduate to be placed

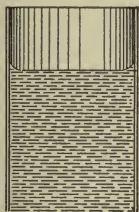


FIG. 5.

under it, set the can near the edge of the table with the spout projecting over the edge. Fill the can till the water begins to run out of the spout, with the graduate under the spout to catch

the overflow; then empty the graduate and again hold it under the spout, as you lower the solid into the can by means of the string. In measuring the overflow, hold the eye on a level with the surface of the water (Fig. 5), and read the scale at the level of the lowest part of the surface (seen through the elevated ridge

¹ Substitute in your record the name of the solid used.

of water at the edge). In taking the reading estimate to tenths of the smallest division.

Data and Computations.—Record each item on a separate line, as in the first experiment, and compute the density of the solid. If its density is given in Table I of the Appendix, compute the percentage of error of your result (Art. 16).

EXERCISE 2. DENSITY OF LIQUIDS

References.—The same as for Exercise 1.

Experiment 3.—*To find the density of water at the temperature of the laboratory.*

Apparatus.—Beam balance and set of weights to 1 cg. (or platform balance and weights to 5 g.); forceps; beaker; 100-c.c. graduate; mop cloth.

Experimental Work.—A measured volume of water is to be weighed in the beaker. Measure in the graduate between 90 and 100 c.c. of water (Fig. 5). In reading the volume it is necessary to have the graduate exactly vertical, and to be sure of this it should stand on the table. Read accurately to the nearest tenth of a cubic centimeter. (An error of one tenth of a cubic centimeter affects the result as much as an error of a decigram in weighing).

Weigh in the beaker the measured volume of water. Be careful to empty the graduate to the last drop. (There are only about ten drops of water in a cubic centimeter.) Weigh the beaker empty and dry.

Data and Computations.—Compute the density of the water. The true density of pure water at 20° C. (which is about the usual temperature of the laboratory) is .998 g. per cubic centimeter. Compute the percentage of error of your result. If this is over 1 %, repeat the experiment. (A large error is almost certainly due to an inaccurate reading of the volume. Why?) Record as follows:—

Volume of water used		=	— cc.
Weight of beaker and water		=	— g.
Weight of beaker empty		=	— g.
Weight of the water	= () — ()	=	— g.
Computed density of water	= () ÷ ()	=	— g. per c.c.
True value of density (at 20° C.)		=	.998 g. per c.c.
Error	= () — ()	=	— g.
Percentage of error	= () ÷ () × 100 %	=	— %.

Experiment 4. — *To find the capacity of a bottle, making use of the known density of water.*

Apparatus (for Experiments 4 and 5). — Beam balance and-set of weights to 1 cg. (or platform balance and weights to 5 g.); bottle of about 2 oz. capacity, with glass stopper; supply of pure water; supply bottle of some liquid (saturated solution of zinc sulphate or table salt, alcohol, or mercury); a jar of water for rinsing; mop cloth.

Experimental Work. — Weigh the bottle empty with the stopper. Fill it with pure water (not from the jar for rinsing) and insert the stopper, being careful to avoid a bubble of air under the stopper. Wipe the outside of the bottle dry and weigh. Return the water to the supply vessel, and stand the bottle on the table inverted to drain.

Data and Computations. — Compute the weight of water that the bottle holds. What is the capacity of the bottle in cubic centimeters, assuming the density of water to be 1 g. per cubic centimeter? Record each item on a separate line, as in the preceding experiment.

Experiment 5. — *To find the density of a liquid,¹ using a bottle of known capacity.*

Experimental Work. — Fill the bottle used in the preceding experiment with the liquid provided, exercising the same precautions as before, and weigh. Return the liquid to the supply bottle,

¹ Substitute the name of the liquid in your record.

rinse the bottle used, and leave it empty. Use the mop cloth, and leave the table and scale pans dry.

Data and Computations.— Compute the weight of the liquid contained in the bottle, and from this and its volume (the capacity of the bottle) compute its density. If its density is given in the Appendix, compute the percentage of error of your result.

Discussion (Oral).— 1. Why will more accurate results be obtained in Experiment 3 by using about as much water as the graduate will measure instead of only a few cubic centimeters?

2. Do you think it would be more or less accurate to find the volume of a liquid by the method of Experiments 4 and 5 than it would be with a graduate, as in Experiment 3? Why?

III. MECHANICS OF FLUIDS

EXERCISE 3. GRAVITY PRESSURE IN LIQUIDS

References. — Adams, 157-159, 163, 165-168 ; Coleman, 21-25 ; Car. & C., 123-124, 127-128 ; Ches. G. & T., 47-49 ; Hoad. Br., 131, 134-137 ; Hoad. El., 140-141, 143-146, 151 ; Mumper, 26-27, 29-31 ; Mil. & G., 57-60 ; Went. & H., 63-64, 68.

Experiment 6. — *To study the pressure of a liquid due to its weight (gravity pressure), with reference especially to the change of pressure with change of depth below the surface.*

Apparatus (for Experiments 6 and 7). — Battery jar containing water ; gas-lamp chimney or student-lamp chimney, with an end ground to fit a plane surface ; small square of cardboard ; a stick 1 ft. long ; two beakers, one low and wide, the other tall and slender, of about the same weight but very unequal diameters.

Experimental Work. — *a.* Place the piece of cardboard over the ground end of the chimney, and lower this end into the jar of water. Hold the chimney loosely so that it will not overturn, and let it sink as far as it will. What keeps it from sinking to the bottom ? Hold the chimney in this position, put the stick down through it, and note the force required to push the cardboard away from the bottom. Is the chimney now sustained by the water as it was when the cardboard was in place ?

Repeat the above or vary the experiment in any way that may occur to you, until you have discovered all that you can in regard to the way in which the chimney is sustained in the water. State briefly the facts observed and your conclusions from them.

b. With the cardboard over the lower end of the chimney as before, push it slowly down to the bottom of the jar, at the same time noting the change in the tendency of the chimney either to

sink farther or to rise. What relation do you observe between the force (pressure) exerted by the water and the depth at which the force is exerted? (Statements of definite or quantitative relations are not supported by this experiment and the two following, since no measurements are made.)

Experiment 7.— *To observe whether the total pressure varies with the area of the surface pressed upon.*

Experimental Work.— With the beakers empty and one in each hand, push them, bottom down, into the water to equal depths, until the water comes nearly to the top of the shorter one. Note which requires the greater downward pressure to hold it in place. Explain.

Experiment 8.— *To observe the effect of the density of a liquid upon the pressure exerted by it at a given depth.*

Apparatus.— Tumbler containing mercury; tumbler of water; two wooden blocks of the same shape and size, and small enough to go into the tumblers; piece of iron.

Experimental Work.— *a.* Compare the weight of the mercury and the weight of the water by lifting the tumblers. (Mercury is 13.6 times as dense as water.) Float one of the blocks on the water and the other on the mercury. Account for the difference in the depths to which the two blocks sink.

b. Push the blocks down till they are submerged in the liquids. Compare the forces necessary to do this, and account for their difference.

c. Put the piece of iron into the mercury. What happens to it? Explain.

Experiment 9. *To measure the pressure in water at different depths with a pressure gauge, or manometer.*

Apparatus.— Hydrometer jar filled with water; two manometers, one containing water, the other mercury; metric rule.

[To reduce capillary action, the manometer tubes should have an internal diameter of at least one fourth inch.]

Experimental Work. — *a.* • Lift the manometer containing water out of the jar, and compare the level of the water in the two arms of the bend. Slowly lower the manometer into the jar of water, and observe the behavior of the water in the bend of the tube. Describe and account for its motion. How is the pressure of the water in the jar transmitted to the water in the manometer?

b. With the manometer held in a fixed position, measure the difference of level, ab (Fig. 6), of the water in the two arms of the bend, and the difference, cd , between the level of the water in the jar and the water in the lower end of the manometer. Take two other pairs of measurements with the manometer at different depths.

Copy Figure 6 in your note book, and record the measurements as follows : —

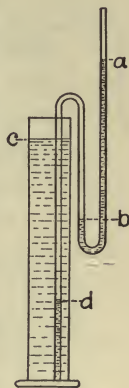


FIG. 6.

	1ST POSITION	2ND POSITION	3RD POSITION
Diff. of level ab	—— cm.	—— cm.	—— cm.
Diff. of level cd	—— cm.	—— cm.	—— cm.

How do the distances ab and cd for any position of the manometer compare? Account as fully as possible for this relation.

c. Repeat the experiment with the mercury manometer, taking three sets of measurements as before. Divide cd by ab for each position. Why is this quotient approximately equal to the density of mercury? Suggest possible reasons why the equality is not exact.

EXERCISE 4. BUOYANCY OF LIQUIDS

References. — Adams, 183-187; Coleman, 30-32; Car. & C., 134-138; Ches. G. & T., 55-57; Hoad. Br., 143-144; Hoad. El., 154-155; Mumper, 40-41; Mil. & G., 74-75; Went. & H., 72-74.

Apparatus. — Specific gravity balance and weights to 1 cg., or platform balance and weights to 5 g.; for the platform balance a

support as shown in Figure 7 ; overflow can ; beaker or tumbler ; jar of water ; jar of solution of table salt ; stone with attached thread ; block of wood ; mop cloth.

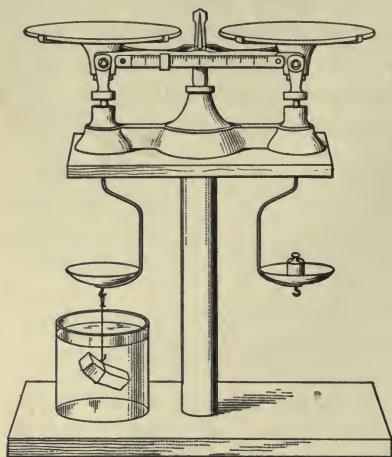


FIG. 7.

Suspend the stone from the hook on the under side of the higher scale pan, and let it hang entirely immersed in the jar of water. Be careful to keep it free from the sides and bottom of the vessel. (If a platform balance is used, adjust as shown in Figure 7.) Weigh it thus. This is called the weight of the stone in water. The difference between this and the weight of the stone in air is the buoyant force upon the stone. (Why ?)

Weigh the stone again, entirely immersed in water as before, but with a greater or a less depth of water above it than before.

Data and Computations. — Record the measurements in the form indicated below, and compute the quantities required : —

Weight of the stone	=	g.
Weight of the beaker	=	g.
Weight of beaker and displaced water	=	g.
Weight of stone in water	=	g.
Weight of stone at a greater depth in water	=	g.

Experiment 10. *To find the relation between the buoyant force exerted upon a stone in water and the weight of the water it displaces.*

Experimental Work. — Weigh the stone and the beaker. Catch in the beaker the water displaced by the stone, when lowered by means of a string into the overflow can filled with water (as in Experiment 2). Weigh the displaced water.

COMPUTATIONS

Weight of water displaced by the stone	=	g.
Buoyant force upon the stone	=	g.
Percentage of difference between the buoyant force and the weight of the displaced water	=	%.

Discussion. — 1. Your results should show (within a small error) a simple relation between the weight of the displaced water and the buoyant force upon the stone. State the true relation.

2. What is likely to be the principal source of error in the experiment? Why?

3. How is the buoyant force affected by increase of depth after the stone is wholly immersed? Why?

4. When the stone hangs suspended by the thread in water, what forces sustain its whole weight?

Experiment 11. — *To find what differences, if any, result when a saturated solution of table salt is used instead of water in the preceding experiment.*

Experimental Work. — Repeat the above experiment, with the exception of the second weighing in the liquid, using the salt solution instead of water. Be very careful not to mix the water and the solution, and return each to the proper supply vessel.

Comparisons. — 1. State the law of buoyancy that holds for both liquids.

2. In which of the liquids is the buoyant force the greater? Why?

Experiment 12. — *To find the relation between the weight of a block of wood and the weight of water that it displaces when floating.*

Experimental Work. — Weigh the block of wood. Find the weight of water that the block displaces when floating, using the overflow can and beaker. Return all liquids to the labeled supply vessels.

Data and Computations. — Record the measurements in the usual form, and find the percentage of difference between the weight of the block and the weight of the water it displaces.

What results should you expect to obtain if you floated the block in the salt solution?

EXERCISE 5. SPECIFIC GRAVITY OF SOLIDS

References. — Adams, 16, 188-189; Coleman, 33-35; Car. & C., 141-143; Ches. G. & T., 58-60; Hoad. Br., 146-147, 149; Hoad. El., 157-160; Mumper, 42-45; Mil. & G., 76-77; Went. & H., 75.

Apparatus. — Specific gravity balance and weights to 1 cg., or a platform balance and support (Fig. 7), or a 250-g. spring balance; thread; tumbler or jar of water; solid denser and one less dense than water; sinker; mop cloth.

Experiment 13. — *To find the specific gravity of a solid that sinks in water, applying the principle of Archimedes.*

Experimental Work. — Weigh the solid in air. Suspend it from the hook on the under side of the higher scale pan by means of a thread, of such length that the solid will be entirely immersed when the tumbler (or jar) of water is placed beneath the pan. In adjusting the height of the solid, it may be found convenient to change the height of the beam of the balance, which can be done by means of the adjustable rod and thumbscrew. (If a platform balance is used, adjust it as shown in Figure 7.) Air bubbles clinging to the immersed solid must be removed. (Why?) Weigh the solid in water.

Data and Computations. — Compute the specific gravity of the solid. If the specific gravity of the substance is given in Table I of the Appendix, compute the percentage of error of your result. Record as follows, substituting the name of the solid used: —

Weight of the solid in air	=	g.
Weight of the solid in water	=	g.

COMPUTATIONS

Weight of an equal volume of water	=	g.
Specific gravity of the solid	=	
True value of its specific gravity	=	
Error	=	
Percentage of error	=	%

Experiment 14.— *To find the specific gravity of a solid that floats in water, making use of a sinker.*

Method.— In this case a denser body, called a sinker, is attached to the solid to keep it wholly immersed when weighed in water. The buoyant force on the solid, when wholly immersed, is greater than its weight; hence it tends to rise, and so exerts a lifting force on the sinker. The two together, therefore, weigh less in water than the sinker alone.

Experimental Work.— Weigh the solid in air, the sinker in water, and both together in water. Be careful not to leave air bubbles clinging to either immersed body.

Data and Computations.— Record as follows:—

Weight of the solid in air	=	g.
Weight of the sinker in water	=	g.
Weight of the solid and sinker together in water	=	g.

COMPUTATIONS

Amount by which buoyancy upon the solid exceeds its weight	=	g.
Buoyant force upon the solid, or weight of an equal volume of water	=	g.
Specific gravity of the solid	=	g.
True value of its specific gravity	=	g.
Percentage of error	=	%

EXERCISE 6. SPECIFIC GRAVITY OF LIQUIDS¹

References.—Adams, 190; Coleman, 36; Car. & C., 144; Ches. G. & T., 61; Hoad. Br., 150; Hoad. El., 161; Mumper, 46-47; Mil. & G., 78-80; Went. & H., 75.

Experiment 15.—*To find the specific gravity of a liquid by weighing a solid in it and in water.*

NOTE. In Exercise 4 a stone was weighed in water and in a saturated solution of table salt. This gives the necessary data for computing the specific gravity of the salt solution, and hence can be made to serve as the experimental work required in this experiment.

Apparatus.—Specific gravity balance or platform balance and support (Fig. 7); weights; tumbler of water; tumbler of the liquid whose specific gravity is to be found; a solid denser than water or the liquid, and insoluble in both (a glass stopper serves well); mop cloth.

Method.—By applying the principle of Archimedes, we find the weight of the liquid displaced by the solid when immersed in it and the weight of water displaced by the same solid. These are weights of equal volumes of the liquid and water. (Why?) Hence, dividing the one by the other, we have the specific gravity of the liquid.

Experimental Work.—Weigh the solid in air, then in the liquid whose specific gravity is to be found. Wipe it dry, then weigh it in water.

Data and Computations.—Substitute in your record the name of the solid and the liquid used in the experiment.

Weight of the solid in air	=	g.
Weight of the solid in the liquid	=	g.
Weight of the solid in water	=	g.

¹ It is not expected that the pupils will perform the four experiments of this exercise in one laboratory period. The teacher may select from them material for one laboratory exercise, or devote two periods to the four experiments.

COMPUTATIONS

Weight of a volume of the liquid equal to the volume of the solid	=	g.
Weight of an equal volume of water	=	g.
Specific gravity of the liquid	=	g.

Experiment 16. *To find the specific gravity of a liquid by balancing columns.*

Apparatus. — One or more U-tubes, each containing water and another liquid that will not mix with water (Fig. 8) ; meter stick, or metric scale, attached to the support of the tube.

Method. — Figure 8 represents a tube containing kerosene, ab , and water, bnm , extending from b round the bend to m . The column of water below b on the one side exactly balances the water *up to the same level, n* , on the other side ; hence the column of kerosene ab balances the column of water mn . In other words, these columns cause equal pressures at b and n respectively.

Let d denote the density of water, d' the density of the kerosene, h the height of the water column mn , and h' the height of the kerosene column ab . Then the pressure at b is $d'h'$ and the pressure at n is dh . (How do we know this?) These pressures are equal, as stated above, *i.e.*

$$d'h' = dh;$$

from which

$$\frac{d'}{d} = \frac{h}{h'}.$$

By definition, the specific gravity of the kerosene is $\frac{d'}{d}$. In the experiment the lengths of the columns h and h' are measured ; and the above equation shows that the ratio of one to the other (of which to which?) gives the specific gravity of the kerosene.

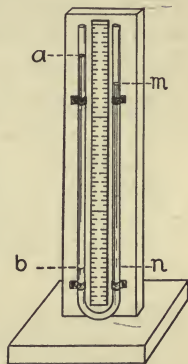


FIG. 8.

Experimental Work. — Find by the above method the specific gravities of the different liquids provided. The measurements to be taken are the heights of the columns above the level of the surface separating the liquids. Make a drawing of the U-tube and its contents in your note book, lettering it as in Figure 8.

Experiment 17. — *To find the specific gravity of a liquid by floating a wooden prism in it and in water, and measuring the displacement.*

Apparatus. — Demonstration hydrometer (wood prism of 1 sq. cm. cross section and graduated in centimeters, or one half inch square and graduated in inches); hydrometer jar containing water and one containing a saturated solution of table salt or other liquid; mop cloth.

Method. — The same body displaces *equal weights* of all liquids in which it floats. (How do we know?) Let w denote the weight of the wood prism, d the density of water, d' the density of the other liquid, v the volume of water displaced by the prism when floating, and v' the volume it displaces in the other liquid; then

$$w = v'd' = vd. \quad (\text{Why?})$$

From which

$$\frac{d'}{d} = \frac{v}{v'}.$$

Hence by this method the specific gravity of the liquid is the ratio $\frac{v}{v'}$. (The ratio of what to what?)



FIG. 9.

Experimental Work. —

Float the prism in water and measure the depth to which it sinks. If the water curves up at the edge

where it comes in contact with the prism, read the scale while looking through the water along the under side of its surface (Fig. 9). Wipe the prism dry, and measure the depth to which it sinks in the other liquid. Remove the prism and wipe it.

Data and Computations.—Compute the displaced volume of each liquid. (The prism, if graduated in centimeters, has a cross section of 1 sq. cm.; if graduated in inches, its cross section is $.5 \times .5$ in.) Record as follows:—

Depth to which the prism sinks in water	=	cm.
Depth to which the prism sinks in the liquid	=	cm.

COMPUTATIONS

Volume of the displaced water	=	cc.
Volume of the displaced liquid	=	cc.
Specific gravity of the liquid	=	--
True value of the specific gravity	=	
Percentage of error	=	%

Experiment 18.—*To find the specific gravity of liquids by means of a common hydrometer.*

Apparatus.—Hydrometer jars containing water and kerosene, alcohol, or other liquids; two common hydrometers, with specific gravity scale, one for light and one for heavy liquids; jar of rinse water; mop cloth.

Experimental Work.—Study the scale on either hydrometer. It is graduated so that its reading at the surface of any liquid in which it floats is the specific gravity of the liquid. Does the reading increase toward the top or the bottom? Why? Find from the numbered divisions the value of the smallest interval. Is this value the same at all parts of the scale? Why does the space between the lines grow smaller toward the bottom? Take the reading of the hydrometer in water, with the eye in the position shown in Figure 9. If this reading is 1000, call it 1. Find the value of the smallest division on the other hydrometer. One of these instruments is for liquids denser than water, and the other for liquids less dense.

Find the specific gravities of all the liquids provided. Rinse and wipe the hydrometer before putting it from one liquid into another, and before putting it away.

EXERCISE 7. PRESSURE OF GASES

References.—Adams, 170-174; Coleman, 34-41, 45; Car. & C., 145-147; Ches. G. & T., 66-67, 70, 77; Hoad. Br., 151-160, 168; Hoad. El., 162-173, 180; Mumper, 34-38; Mil. & G., 81-87; Went. & H., 76-78, 80.

Experiment 19.—*To study the transmission of pressure in fluids by means of the Cartesian diver.*

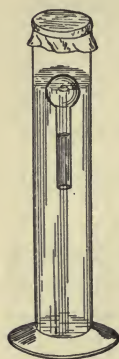


FIG. 10.

Apparatus.—An hydrometer jar nearly full of water, in which is floated a short glass tube with a bulb blown at one end, inverted and containing just enough air to float it (the water must only partially fill the tube); sheet rubber tied air-tight over the jar.

[A satisfactory substitute for the tube and bulb is shown in Figure 11. It consists of a test tube, fitted with a rubber stopper through which a piece of quarter-inch glass tubing is inserted. The test tube is partly filled with water, the right amount being determined by trial.]



FIG. 11.

Experimental Work.—Press down on the rubber cover of the jar with the fingers, and increase the pressure till the floating tube sinks. Diminish the pressure till the tube rises. Repeat and observe the change of level of the water in the tube as you vary the pressure with the fingers. Describe and account for this change of level. What does it prove concerning the transmission of pressure by air and water? Explain the sinking and rising of the tube.

Experiment 20.—*To study the principle of the barometer.*

Apparatus.—A bottle with a two-hole rubber stopper, fitted with a glass tube in one hole and a round plug in the other; jar of water; three tumblers, one containing mercury; a Y-tube, con-

connected with two glass tubes of unequal diameter and about 100 cm. long, the free end of the Y-tube fitted with a piece of rubber tubing and pinchcock (Fig. 12) ; meter rod ; tall iron stand and clamp, or other support ; mop cloth.

Experimental Work. — *a.* Fill the bottle with water and insert the stopper. See that no air remains in the bottle. With the glass tube in one hole of the stopper and the plug tightly in the other, apply the mouth to the tube and try to “draw” water from the bottle as you would soda water through a straw. State and account for the result. Do you find any evidence that the “suction” exerted on the water in the tube consists of a pulling force?

b. Remove the plug from the second hole of the stopper, and repeat the experiment. State and account for the result, avoiding the use of such indefinite terms as “draw,” “suck,” and “suction.”

c. Place the long glass tubes in two tumblers of water, as shown in Figure 12 ; and, with the pinchcock open, apply the mouth to the end of the rubber tube and exhaust the air till the water rises nearly to the top of the tubes. Close the pinchcock and remove the mouth from the tube. Open the pinchcock. Describe and account for all that has taken place in the tubes.

d. Again exhaust the air as before, and take the following measurements, using the stand and clamp to hold the tubes in the required positions : —

With both tubes vertical, measure the height of the column of water in each, measuring from the level of the water in the tumbler.

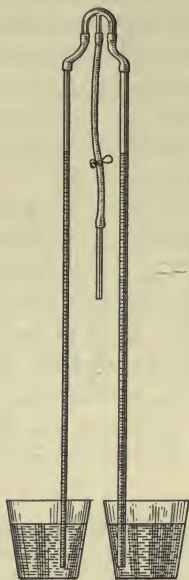


FIG. 12.

With one tube slightly inclined and the other very oblique, measure the length of each column along the tube.

Without changing the position of the tubes, measure the vertical height of each column above the level of the water in the tumblers. (It will be most convenient to measure the height of the columns above the table, and afterwards subtract the height of the water in the tumblers, also measured from the level of the table.) Record the measurements in tabular form, and make a sketch of the apparatus.

2. Open the pinchcock and let the water run out of the tubes. Substitute the tumbler of mercury for one of the tumblers of water, exhaust the air from the tubes till the water rises nearly to the top of its tube, and close the pinchcock. With the tubes vertical, measure the height of the water and mercury columns above the level of the liquids in the tumblers. Empty the tubes and remove them from the tumblers.

• Compute the ratio of the height of the water column to the height of the mercury column.

Discussion. — 1. What causes the water to rise in the tubes when the air is partially exhausted?

2. How would you find in grams per square centimeter the difference between the pressure of the air remaining in the tubes and the pressure of the outside air?

3. What effect has the diameter of the tube on the height to which the water rises? How would the result be affected if the larger tube had a diameter of several centimeters?

4. What effect has the unequal inclination of the tubes on the vertical height of the water in them? Explain.

5. Account for the relative heights of the water and mercury columns in the last part of the experiment.

6. Suggest a modification of the experiment by which the tube containing mercury would become a barometer. What further modification would be necessary to make the tube containing water a water barometer?

Experiment 21.— *To determine the degree of exhaustion that the pupil can produce with his mouth.*

Apparatus.— A mounted, open-tube manometer containing mercury (Fig. 13), the arms of which are at least 40 cm. long ; a heavy-walled piece of rubber tubing attached to the manometer, with a short piece of glass tubing at its free end. Or, instead of the preceding, a piece of glass tubing 40 to 50 cm. long, with a piece of rubber tubing attached, in the other end of which a short piece of glass tubing is inserted; tumbler containing mercury ; meter rod.

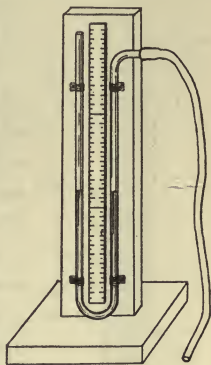


FIG. 13.

Experimental Work.— Apply the mouth to the rubber tube, and exhaust the air as fully as possible. This may be done in stages, closing the tube between the efforts either by placing the tip of the tongue against the end of the tube or by pinching the tube in the fingers. Be very careful not to draw the mercury up into the mouth. Measure, in the most convenient way that occurs to you, the greatest difference of level of the columns that you can produce. (If the straight glass tube and tumbler of mercury are provided instead of the manometer, hold the tube in a vertical position, with its lower end in the mercury, and proceed as above.)

Assuming that the atmospheric pressure is 76 cm., compute the fraction of the whole pressure that you removed by "suction."

EXERCISE 8. BOYLE'S LAW

References.— Adams, 177-178; Coleman, 44-47; Car. & C., 161-163; Ches. G. & T., 75-76; Hoad. Br., 166; Hoad. El., 178; Mumper, 39; Mil. & G., 95; Went. & H., 79.

Experiment 22.— *To find the relation between the volume of a given mass of air and the pressure exerted upon it.*

Apparatus. — A Boyle's Law apparatus with adjustable closed and open tubes (Fig. 14).

Method. — **NOTE.** No record is required of the following experimental study of the method of using the apparatus. If the apparatus has been discussed in class, this experimental study of it may be omitted.

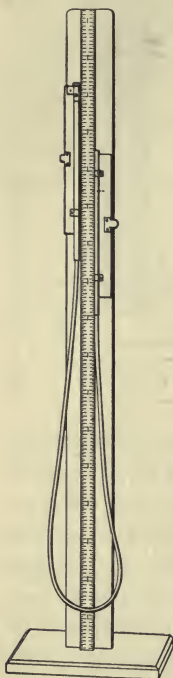


FIG. 14.

Adjust the open and closed tubes so that the mercury stands approximately at the same level in both. What evidence is there that the closed tube contains a gas above the mercury? It is air. How would the mercury stand in the closed tube if the air were removed?

From the fact that the mercury stands at the same level in the two arms, what do you know concerning the relative value of the air pressure upon the two mercury surfaces?

Raise the open tube 20 or 30 cm., and while doing so, observe the change of level of the mercury in the closed tube. Has the confined air increased or diminished in volume? Has the pressure upon it been increased or decreased, and from what cause? If we let H denote the height of the barometer and d the difference of level of the mercury in the two arms, then $(H + d)$ cm. of mercury measures the pressure upon the confined air. Why?

Lower the open tube 50 cm. or more, while watching the change of level of the mercury in the closed tube. How is the volume of the confined air changing? Why is it changing? Again letting d denote the difference of level of the mercury columns, the pressure upon the confined air is now $(H - d)$ cm. of mercury. Why?

Experimental Work. — *a.* Clamp the closed tube near the bottom of the standard, and leave it in this position for the first three

sets of readings. Adjust the open tube so that the mercury stands at exactly the same level in both tubes. Take a set of readings as indicated in the tabular form below. "Reading of top of closed tube" means the reading of the meter rod at the level of the top of the air space in the closed tube. If the end of the air space is round, estimate the position to which it would extend if it were squared off without changing the volume. The readings called for will be more accurately found by holding the straight edge of a piece of paper across from the tube to the meter rod.

b. Raise the open tube and clamp it at about the middle of the standard. Take a second set of readings.

c. Again raise the open tube and clamp it near the top. Take a third set of readings.

d. Raise the closed tube and clamp it with its upper end near the top of the standard. Lower the open tube and clamp it at about the middle of the standard. Take a set of readings.

e. Lower the open tube and clamp it near the bottom. Take a set of readings. Leave the tubes clamped at about the same height, and in such a position that the tube rests upon the base.

f. Read the laboratory barometer. This reading is denoted in one of the headings of the tabular record by *H*.

Data and Computations. — Record as indicated below, and perform the indicated computations. Since the closed tube is of uniform bore, the volume of any portion of it is proportional to the length of that portion; hence the length of the air column may be taken to represent its volume. This is done in the record, where the length of the air column is denoted by *V*.

SET	READING OF TOP OF CLOSED TUBE	READING OF TOP OF MERCURY COLUMN	
		In closed tube	In open tube
<i>a</i>	— — cm.	— cm.	— — cm.
<i>b</i>	— cm.	— cm.	— cm.
etc.	— cm.	— cm.	— cm.

f. Height of the barometer, *H* = — cm.

COMPUTATIONS

SET	LENGTH OF AIR COLUMN, OR V	DIFFERENCE OF LEVEL OF MERCURY COLS. = d	PRESSURE = $H \pm d = P$	PV
a	— cm.	— cm.	— cm. (of mer.)	—
b	— cm.	— cm.	— cm. (of mer.)	—
etc.	— cm.	— cm.	— cm. (of mer.)	—

Discussion. — 1. According to Boyle's Law, what relation should exist among the numbers of the column headed PV (the product of pressure and corresponding volume)?

2. Compute the percentage of difference between the greatest and the least of these numbers. With fair apparatus and reasonably careful work, this difference will not exceed 2 %.

EXERCISE 9. THE SUCTION PUMP AND THE SIPHON

References. — Adams, 179-181; Coleman, 49, 51, 53; Car. & C., 157-160; Ches. G. & T., 80, 82, 84; Hoad. Br., 169-170; Hoad. El., 182-184, 189; Mumper, 48-51; Mil. & G., 99, 102, 104; Went. & H., 84, 86, 88.

Experiment 23. — *To study the action of a suction pump.*

Apparatus. — A glass suction pump; battery jar of water; mop cloth.

Experimental Work. — CAUTION. In working the piston of the pump, always push and pull directly in line with its length. The rod is easily broken with careless handling. Work the piston slowly, never using more than a moderate force, and be careful not to strike the pump against the bottom or side of the jar.

Starting with the pump empty, place the lower end in the jar of water, and work the piston slowly. Note when the water begins to rise in the tube of the pump. What causes it to rise? (Any reference to "suction" explains nothing.) Observe the behavior

of the valves during the downstroke and the upstroke of the piston. Operate the pump till you understand the motion and use of the valves. To empty the pump, raise it above the water, pull the piston up, turn the pump so that the water above the piston will run out of the spout, turn the lower end of the pump slightly upward and shake the lower valve out of position, then turn the lower end slightly downward, and the water will run out. Leave the pump empty and place it on the table.

Draw two figures of the pump — one showing the position of the valves during the upstroke of the piston, the other their position during the downstroke. Write a brief description of the action of the pump, referring to your drawings for illustration.

Experiment 24. — *To study the action of a siphon.*

Apparatus. — Siphon made of glass tubing of not less than $\frac{1}{4}$ in. bore, with arms of unequal length and at an angle of about 50° to each other; two battery jars with water, or better, one jar and sink at which to work; small beaker; mop cloth.

Experimental Work. — *a.* Invert the siphon and fill it from the beaker by pouring into one arm and closing the end of the other arm with a finger, after it is filled. When both arms are full, stop each end with a finger, and turn the siphon right side up (*i.e.* with the bend at the top). Observe the effect of removing the finger from either end, leaving the other end closed. State and account for the result.

b. Hold the ends of the siphon over the jars, with the end of the longer arm lower than the other, and remove the fingers from both ends. From which end does the water run? Repeat with the end of the shorter arm lower than the other. Does the water always run out of the longer arm? Does it always run out of the lower end, whichever that may be? Repeat till you are sure of the answer.

c. Place one of the jars, with water in it, on some support above the other jar. Siphon the water from this jar into the lower one. While the siphon is running, note the effect of tilting it so

as to vary the height of the outer end. Try the effect of slowly raising the outer end up to and above the level of the surface of the water.

Discussion. — 1. What determines from which end of the siphon the water will run ? Why ?

2. Is the rate of flow more or less rapid when the outer arm of the siphon is lowered ? Why ?

3. Why does the water not part at the top and fall from both ends when a siphon is started ?

IV. STATICS OF SOLIDS

EXERCISE 10. EQUILIBRIUM OF CONCURRENT FORCES

References.—Adams, 47-54; Coleman, 57-65; Car. & C., 40-44; Ches. G. & T., 103-106; Hoad. Br., 47, 49; Hoad. El., 54, 56; Mumper, 58-60, 64, 67; Mil. & G., 23-26; Went. & H., 41-45.

Experiment 25.—*To study the conditions for equilibrium of three concurrent forces.*

Apparatus.—Three 2000-g. spring balances, with flat backs or provided with some simple support to keep them level when lying on the table; three short cords tied to a small ring; rule; a broad board, with narrow strips on two adjacent sides, in which are holes 1 in. apart, together with two nails and a clamp (Fig. 15).

[Where clamps can be attached to both sides of the table (Fig. 16), three clamps and three blocks with hooks can be used instead of the board. With three tension clamps (Fig. 17) the blocks with hooks are unnecessary.]

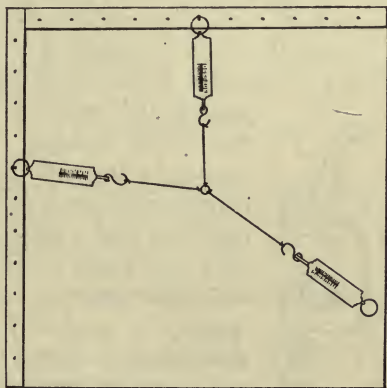


FIG. 15.

FIRST CASE: *When none of the angles between the directions of the forces are specified.*

Experimental Work.—If the board shown in Figure 15 is provided, fasten two of the balances by their rings to nails inserted

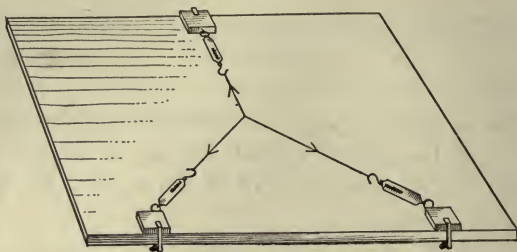


FIG. 16.

in holes in the board, and clamp the third balance in position, passing the screw of the clamp through the ring of the balance. If three clamps and three blocks are provided, clamp the blocks to the table, and adjust as shown in Figure 16.

Attach the cords on the ring to the hooks of the balances. Fasten the balances in position so that the pull on each is between 1000 g. and 2000 g. The forces and the angles may all be unequal. See that the balances lie exactly in line with the cords. (Why?) Place a large sheet of paper under the cords with its center under the ring. Hold the paper in a fixed position while you make a small dot exactly at the point under the ring over which the three cords would intersect if produced across the ring, and a dot directly under each of the cords at a distance of not less than 8 or 10 cm. from the ring. The purpose of these dots is to determine the directions of the

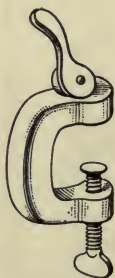


FIG. 17.

cords with the greatest possible accuracy. Have the pencil sharp and make the dots small. In locating a dot, the eyes must be vertically above the cord, and the cord should be very near the paper.

Without disturbing the balances, take the reading of each, and record the forces on the sheet beside the corresponding cords. Estimate the readings of the scales to tenths of the smallest division.

Construction.—The diagram based on the above record may be constructed on the sheet used and transferred later to the note book; or the record may be transferred to the note book at once by laying the sheet flat on a page of the note book and pricking a pin point through each of the dots.

The construction must be an accurate record of experimental results. It is as follows: Draw lines through the dots indicating the directions of the three cords (and hence also the directions of the forces exerted upon the ring). Call the point of intersection of the lines O . Measure off on the lines from O distances proportional to the forces, using a scale that will give a rather large figure. A scale of 200 g. to the centimeter is about the best. Record the scale adopted near the diagram. Construct a parallelogram upon any two of the lines whose lengths have thus been determined, taking the lines as sides of the parallelogram. For convenience the force represented by the line not used in this construction will be referred to as the third force. Draw the diagonal of the parallelogram extending from O . Measure the length of this diagonal, and find, from the scale adopted, the magnitude of the force it represents.

Record beside each of the four lines extending from O its length in centimeters and the magnitude of the force it represents in grams. Indicate the directions of the forces by arrowheads.

Discussion.—1. What force is represented by the diagonal of the parallelogram?

2. How should this line compare in magnitude and direction with the line representing the third force?

3. In what respects and to what extent do the relations shown in your diagram differ from the true relations? Draw the angle that measures the error in the direction of the diagonal, assuming the direction of the third line from O to be correct.

SECOND CASE: *When the angle between the directions of two of the forces is 90° .*

Experimental Work. — Repeat the experiment, with the balances adjusted so that two of them will act at an angle of exactly 90° after the forces are applied, none of the forces being less than 1000 g. Measure the angle with a piece of paper folded so that the two parts of a straight edge coincide.

Construction. — Using the same method as before, find the resultant of the two forces acting at an angle of 90° . Record all lengths and the forces represented by them in the diagram.

Computation and Comparison. — 1. Find the same resultant by computation. (The square on the hypotenuse of a right triangle is equal to the sum of the squares on the other two sides.) Remember that the resultant is a force, not a line.

2. Write down for comparison: —

The resultant found by construction	=	g.
The resultant found by computation	=	g.
The equilibrant (reading of the third balance)	=	g.

Compute the percentage of difference between the largest and the smallest of these quantities. This difference is due to experimental errors. What are the probable sources of error?

EXERCISE 11. EQUILIBRIUM OF PARALLEL FORCES

References. — Adams, 55; Coleman, 67–68; Car. & C., 46; Ches. G. & T., 90–95; Hoad. Br., 51; Hoad. El., 60; Mumper, 64; Went. & H., 53.

Experiment 26. — *To study the conditions for equilibrium of three parallel forces.*

Apparatus. — Meter rod; two 2000-g. spring balances; two unequal weights of about 2000 g. and 3000 g., respectively; cord; frame to support the balances (Fig. 34); rule.

Method. — The three parallel forces to be studied act upon a meter rod. Two of them are exerted by spring balances, and the other by a weight (Fig. 18). The weight of the rod itself is an additional force which necessarily affects the readings of the balances; but since this force is not included in the problem

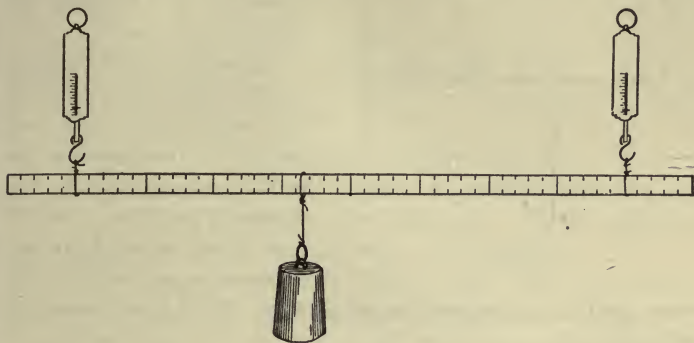


FIG. 18.

under consideration, it is eliminated by subtracting from all readings of the balances the forces exerted by the balances in supporting the rod alone.

Experimental Work. — *a.* Adjust the balances and meter rod as shown in Figure 18, but without the weight attached. The supporting cords must be vertical. For convenience in reading the distances, the balances may be hung 80 cm. apart and the cords attached to the rod 10 cm. from each end. Take the readings of the balances when supporting the rod only. Record the readings as the *zero readings* of the left and right scales, respectively. These are the forces necessary to support the weight of the rod, and they are to be subtracted from all later readings of the scales in order to obtain the forces necessary to balance the weight that is hung on the rod. In order to keep the zero readings the same throughout the experiment, the rod must always be supported from the same points.

In Figure 19, A and B denote the points of support of the rod, and C the point where the weight hangs. In this figure, and also in the record, d_1 denotes the distance AC , d_2 the distance CB , W the attached weight, and f_1 and f_2 the forces necessary to balance

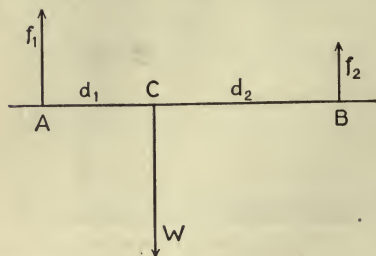


FIG. 19.

W (not including the forces necessary to balance the weight of the rod).

b. Hang one of the weights on the rod midway between the supporting cords, and record the readings of the scales and the equal distances d_1 and d_2 .

c. Move the weight 10 cm. or more to one side of the center, and take a second set of readings (*i.e.* the scale readings and d_1 and d_2).

d. Take a third set of readings, using the other weight and placing it in a new position on the rod. Remove the weight.

Draw a figure for each set of readings taken, similar to Figure 19, representing the distances and the forces approximately to scale. (An accurate construction is not required.)

Data and Computations. — Record measurements and computations as follows: —

a. ZERO READINGS: Left Scale = — g. Right Scale = — g.					
SET	SCALE READING		W	d_1	d_2
	Left	Right			
<i>b</i>	— g.	— g.	— g.	— cm.	— cm.
<i>c</i>	— g.	— g.	— g.	— cm.	— cm.
<i>d</i>	— g.	— g.	— g.	— cm.	— cm.

COMPUTATIONS

SET	FORCES		$f_1 \div f_2$	$d_2 \div d_1$	Difference	% of Diff.	$R=f_1+f_2$	$R - W$
	f_1	f_2						
<i>b</i>	— g.	— g.	—	—	—	— %	— g.	— g.
<i>c</i>	— g.	— g.	—	—	—	— %	— g.	— g.
<i>d</i>	— g.	— g.	—	—	—	— %	— g.	— g.

Discussion. — 1. The difference between the ratios $f_1 \div f_2$ and $d_2 \div d_1$ is due to experimental errors. It should not exceed 2 % unless the spring balances are very inaccurate. If the difference exceeds this, try to discover the source of the trouble.

2. Write the proportion that holds between the true values of the quantities f_1 , f_2 , d_1 , d_2 , and state the proportion in words.

3. What relation holds between the true values of f_1 , f_2 , and W ? What name applied to W expresses its relation to the other two forces?

ALTERNATIVE METHOD

Apparatus. — Meter rod; three 2000-g. spring balances; three clamps and blocks with hooks for holding balances (Fig. 19), or three tension clamps; cord.

General Directions. —

Follow the directions given above, but with the following modifications: A third spring balance is used instead of the weight, and the rod and balances lie on the table (Fig. 20). The three cords must be parallel, and their lengths are to

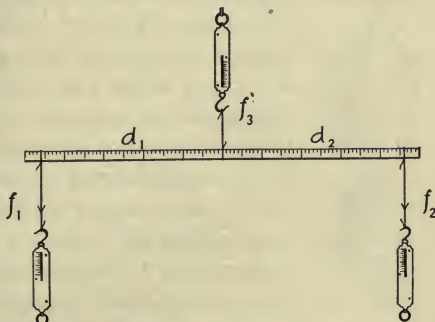


FIG. 20.

be so adjusted that the reading of the single opposing balance is nearly 2000 g. No allowance is required for the weight of the rod, since it is not supported by any of the balances ; hence omit the experimental work of paragraph (a) above.

Before reading the balances, raise the meter rod one or two centimeters, and let it drop. Repeat this several times, so that all parts of the apparatus will come into proper adjustment without hindrance from friction. This is very important. In the diagrams and the record designate the outer forces as f_1 and f_2 and the inner force as f_3 .

EXERCISE 12. MOMENTS OF FORCE

References.—Adams, 108-111 ; Coleman, 69-71 ; Car. & C., 47 a ; Ches. G. & T., 90-93 ; Hoad. Br., 96-98 ; Hoad. El., 106-108 ; Mumper, 66 ; Mil. & G., 208-210 ; Went. & H., 49-51.



FIG. 21.

Experiment 27.—*To study the conditions for equilibrium of two forces with respect to rotation about an axis.*

Apparatus.—Meter rod with hole at 50 cm. ; upright with nail to support the rod ; spring balance ; four weights, two of which are equal ; rule.

[The hole in the rod should be exactly at 50 cm. and slightly displaced laterally, so that the rod will balance horizontally with slight stability on a nail. If one end of the rod is heavier than the other, the defect can be remedied by boring small holes in the heavier end or by means of a sliding wire rider. A 1-kg. weight should be used with a 2000-g. balance, and a 100-g. weight with a 250-g. balance. Either combination will serve. A set of "universal laboratory weights" (Fig. 21) is very convenient for this exercise and those on machines. The set runs from 5 to 1000 g. (C. H. Stoelting Co., Chicago, manufacturers.)]

Experimental Work. — *a.* Hang the meter rod on the nail. Hang one of the equal weights near each end of the rod, and adjust them so that the rod balances in a horizontal position. Let w_1 and w_2 denote the weights, and a_1 and a_2 the respective distances from their points of suspension to the axis (the nail). Record the values of these quantities in tabular form, as given below.

b. Hang two unequal weights on the rod, and adjust them so that they balance. The nearer the weights are to the ends of the rod, the more accurate the results are likely to be. (Why?)

c. Repeat with two other unequal weights.

d. With a 250-g. spring balance use a 100-g. weight for the remaining work; with a 2000-g. balance use a 1000-g. weight, or the largest provided. Hang the weight 20 cm. from an end of the rod, and support the rod on the hook of the spring balance, applied nearer *the same end* of the rod. Let f_1 denote the force applied by means of the balance and a_1 the distance from its point of application to the axis; and let w_2 denote the weight and a_2 the distance of its point of application from the axis.

e. Repeat with the balance applied between the weight and the axis. After recording the set of measurements, try the effect of applying the balance nearer and nearer the axis, until it is as near as you can get it. State the general result of these trials without taking measurements.

Draw a figure for each set of readings, similar to Figure 22, representing the distances and the forces approximately to scale.

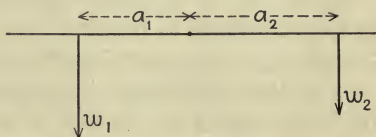


FIG. 22.

f. Adjust the weight and the balance as in either (*d*) or (*e*), with the hook tied to the rod to keep it from slipping, and observe the change in the reading of the balance when the force exerted by it is made more and more oblique to the vertical. Does the *moment* of the force change as the force changes? How do you know?

Does its arm change (while it is still applied at the same point)? What distance is the arm of the force when the force is oblique? Measurements need not be taken.

Data and Computations.—Record in the form given below. Compute the products w_1a_1 (or f_1a_1) and w_2a_2 for each set of measurements, also their difference and percentage of difference.

	w_1	w_2	a_1	a_2	w_1a_1	w_2a_2	Diff.	% of Diff.
<i>a</i>	— g.	— g.	— cm.	— cm.	—	—	—	— %
<i>b</i>	— g.	— g.	— cm.	— cm.	—	—	—	— %
<i>c</i>	— g.	— g.	— cm.	— cm.	—	—	—	— %
	f_1				f_1a_1			
<i>d</i>	— g.	— g.	— cm.	— cm.	—	—	—	— %
<i>e</i>	— g.	— g.	— cm.	— cm.	—	—	—	— %

Discussion.—1. Express, both as an equation and as a proportion, the relation that holds for the true values of the quantities w_1 , w_2 , a_1 , and a_2 ; and also for the true values of w_2 , f_1 , a_1 , and a_2 .

2. State the two conditions necessary for the equilibrium of two forces with respect to rotation about an axis, and word the statement so as to cover every case presented in the experiment.

3. In this experiment we have not had occasion to consider the force exerted on the rod by the nail. What do you know (from the laws studied in Exercise 11) about the magnitude and direction of this force and its effect on the behavior of the rod?

4. Does the force exerted by the nail tend to cause the rod to turn in either direction? Why or why not?

5. In Exercise 11 what forces tend to cause rotation about C as an axis? Why is there not rotation about this point? Prove your answer correct by making use of any one of the sets of measurements taken in that exercise.

EXERCISE 13. CENTER OF GRAVITY AND MOMENT OF WEIGHT

References. — Adams, 61-66; Coleman, 73-75; Car. and C., 51-52, 55-56; Ches. G. & T., 98-100; Hoad. Br., 70-71, 74; Hoad. El., 82-86; Mumper, 68-69; Mil. & G., 33-34; Went. & H., 55-59.

Experiment 28. — *To find whether the point of application of the weight of a body, regarded as a single force, changes, or remains the same, under different conditions.*

Apparatus. — Meter stick; wooden or iron clamp; support with a narrow edge; platform balance and weights.

FIRST CASE: A REGULAR BODY

Experimental Work. — Weigh the meter stick. Balance it in a horizontal position on the sharp edge of the support. The weight of the stick, under these conditions, is evidently equivalent to a single force acting at a point vertically above the support, for it is balanced by the upward pressure of the support. This point, then, is, by definition, the center of gravity of the stick when thus balanced. Record its position as the reading of the meter scale at the axis. (On account of slight variations in the density or cross section of the stick, the reading may not be exactly 50 cm.)

The purpose of the experiment is to determine whether the weight of the stick is equivalent to a single force *acting at this same point*, or whether it must be regarded as acting at some other point, when the stick is balanced in a different way; in other words, to deter-

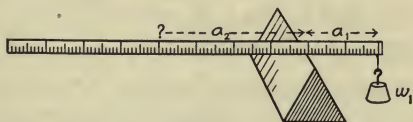


FIG. 23.

mine whether the center of gravity remains fixed or shifts to a new position when the conditions are changed. Balance the stick in a horizontal position on the support as before, but with a 100-g.

weight hanging on it 1 cm. from its *zero end* (Fig. 23). (It is less convenient to calculate distances from the 100-cm. end.) Record the position of the axis as the reading of the meter scale at that point.

Data and Computations. — When the stick is balanced with the attached weight, this weight tends to pull the shorter end of the stick down; while the weight of the stick itself tends to pull the longer end down. Obviously, if we regard the weight of the stick as one force, the stick is in equilibrium under the action of two equal and opposite moments of force; namely, the moment of the attached weight and the moment of the weight of the stick. That is, the product of the attached weight and its arm is equal to the product of the weight of the stick and its arm (the arm of the weight of the stick being the distance from the axis to the point of application of the weight of the stick, wherever that may be).

Let w_1 denote the attached weight, w_2 the weight of the stick, a_1 the arm of the attached weight, and a_2 the arm of the weight of the stick. Then, as stated above, $w_1 a_1 = w_2 a_2$. Since a_2 is the only unknown quantity in this equation, it can be computed; and, measuring off this distance from the axis, we come to the point where the weight of the whole stick *must* be regarded as acting to produce the observed effect. The point thus found is, therefore, the center of gravity under the conditions of the experiment. Is this second position of the center of gravity the same as the first?

Copy Figure 22 in your note book, and record data and computations as follows: —

Weight of the meter stick, w_2	=	g.
Position of the axis when the stick is balanced alone (first position of the center of gravity of the stick)	=	cm.
Attached weight, w_1	=	g.
Position of attached weight	=	1 cm.
Position of axis for equilibrium with weight attached	=	cm.

COMPUTATIONS

Arm of attached weight, a_1	=	cm.
Arm of the weight of the stick (distance from the axis to second position of center of gravity of stick), $a_2 = w_1 a_1 \div w_2$	=	cm.
Second position of center of gravity of stick = position of the axis + a_2	=	cm.
Difference between the first and second positions of center of gravity of stick	=	cm.

Conclusion. — Assuming that experimental errors may reasonably account for a difference of .3 cm. in the two positions found for the center of gravity of the stick, what answer have you found to the question under consideration?

SECOND CASE: AN IRREGULAR BODY

General Directions. — Repeat the above experiment with a clamp firmly attached to the 100-cm. end of the stick, and remaining thus throughout the experiment. The stick and clamp are to be regarded as one irregular body. Weigh this irregular

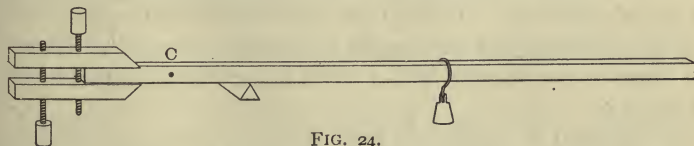


FIG. 24.

body, and find its center of gravity when balanced alone on the axis, and again when it is balanced with a weight of 200 g. to 500 g. attached near the lighter end (Fig. 24). If there is time enough, make two trials, either with different attached weights or with the weight in different positions.

Do the results in this case lead to the same conclusion as before, or to a different one?

EXERCISE 14. CENTER OF GRAVITY AND THE STATES OF EQUILIBRIUM

References.—Adams, 61–69; Coleman, 73–80; Car. & C., 51–52, 55–58; Ches. G. & T., 98–101; Hoad. Br., 70, 71, 74, 75; Hoad. El., 82–87; Mumper, 68–69; Mil. & G., 33–37; Went. & H., 55–57, 60.

Experiment 29. — *To find the center of gravity of an irregular piece of cardboard.*

Apparatus (for Experiments 29 and 30).—Irregular piece of cardboard; pins; small plumb line made of thread and bullet; rule.

Experimental Work. — *a.* Stick a pin through the cardboard near one corner, and enlarge the hole enough to allow the cardboard to swing freely. Stick the pin, with the cardboard on it, horizontally into the edge of the table or other support. Hang the plumb line on the pin in front of the cardboard, but not quite touching it. When both have come to rest, grasp them together at the bottom, make a dot accurately under the thread, and with a sharp pencil and rule draw a line connecting the dot with the point of suspension. How do you know that the center of gravity of the cardboard is at some point on this line, or, more accurately, at some point directly back of this line, midway between the surfaces?

b. Suspend the cardboard from another corner, and determine a second line in the same way. Where is the center of gravity of the body. Would this point be vertically under *any* point of suspension from which the cardboard hangs at rest? Test the matter by suspending the body from a third point, chosen at random. State the result.

c. Trace the outline of the cardboard in your note book, mark the three points of support, and draw the plumb lines. Letter the center of gravity *C*.

Experiment 30. — *To study the states of equilibrium of a suspended body.*

Experimental Work. — *a.* Hang the cardboard again from one of the holes near the edge, turn it out of the position in which it hangs at rest, and release it. How does it behave as it comes to rest? Account for this motion as definitely as you can. In what state of equilibrium does it come to rest? How do you know?

b. Suspend the cardboard exactly at the center of gravity, enlarge the hole till it turns freely, and note its behavior when turned out of a position of rest and released. Does it always come to rest in the same position?

It is not easy to find the center of gravity exactly; it generally happens that the hole is far enough out of position to affect appreciably the behavior of the cardboard. What reason have you, if any, for thinking that such is the case in your experiment? How would the body behave when turned and released, if it were suspended accurately at the center of gravity? Why? In what state of equilibrium would it be when thus suspended and at rest?

c. Suspend the cardboard at one of the outer holes, and try to balance it with the center of gravity vertically above the support. Why is it practically impossible to secure equilibrium in this position? What would equilibrium in this position be called?

Experiment 31. — *To study the states of equilibrium of bodies supported on a horizontal surface.*

Apparatus. — Such bodies as cylinder, cone, sphere, oblate and prolate spheroids; an empty, round-bottom flask; a round-bottom flask loaded with shot so that it will stand upright. (The shot can be kept in place by paraffine or wax melted over it.)

Experimental Work. — *a.* A body may be in different states of equilibrium at the same time with respect to motion in different directions. Experiment with the different bodies provided, and determine their states of equilibrium in different positions, and with respect to motion in different directions for each position.

Give a complete account of each case studied, with drawings to illustrate. Include cases of unstable equilibrium, whether you can

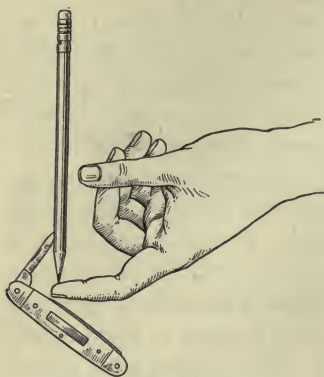


FIG. 25.

perfectly realize them or not. Locate as closely as possible the center of gravity in each drawing, and indicate by a dotted line the path that it would describe if the body were tipped or rolled.

b. Balance your pencil on its point on your finger, making use of a pocketknife to secure stable equilibrium, as shown in Figure 25. Draw a figure showing the position of equilibrium as you secured it, and indicate approximately the position of the center

of gravity of the knife and pencil regarded as one body. How definitely does the experiment determine this center of gravity?

EXERCISE 15. STIFFNESS OF BEAMS. THE TRUSS

References. — Adams, 26, 140–143; Coleman, 202–204, 206; Car. & C., 14–15; Hoad. Br., 27; Hoad. El., 27–30; Mil. & G., 152–156; Mumper, 22; Went. & H., 23–30.

Experiment 32. — *To study the effect of the length and the shape of the cross section of a beam upon its stiffness.*

Apparatus. — Three meter sticks; small rod of steel or brass one meter long, and a tube of the same material, length, and weight.

Experimental Work. — *a.* Note the effort required to bend a meter stick in the hands, while holding it near the ends. Repeat several times, decreasing the distance between the hands with each trial, and observe how difficult the bending becomes as the length of the bent portion is decreased. Account for the observed facts as fully as you can.

b. Holding the rod at the ends, bend it as before in the plane of its smallest dimension (thickness), then in the plane of its width. Compare the stiffness of the rod with respect to bending in these two planes. (Is the stiffness slightly greater, considerably greater, or several times greater in the one case than in the other?) To vary the experiment, rest the ends of the rod on fixed supports (as the edges of two stools), first flatwise, then on edge; and, grasping it firmly at the middle, push down upon it.

When the rod is bent is its inner side stretched or compressed? Is its outer side stretched or compressed? (If in doubt, mark half-inch spaces on the two sides of a long rubber eraser, and observe the change in the length of these spaces when the rubber is bent in the fingers.) Account as fully as you can for the unequal stiffness of the meter rod with respect to bending in the two planes.

c. Place the three meter rods together so as to form a compound rod of approximately square cross section. Test the stiffness of this compound rod with respect to bending in the two planes (Fig. 26). In doing this it will be necessary to place the ends of the rod on fixed supports and push down hard at the middle.

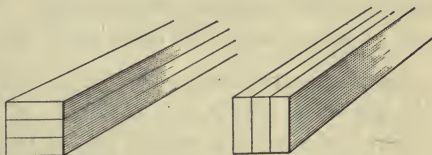


FIG. 26.

Carefully observe whether bending in either position is necessarily accompanied by slipping of one surface over another where the rods are in contact. Account as fully as you can for the unequal stiffness of the set of rods in the two positions.

If the rods were nailed together along their whole length, do you think the stiffness would be increased for the first position shown in the figure? Do you think it would be for the second position? Give reasons for your opinion.

d. Test the relative stiffness of the metal rod and tube, and account for the results. (They contain equal quantities of the same material.)

Experiment 33. — *To assemble the members of a model bridge truss, and to study their function as parts of the whole.*

Apparatus. — A separable model of the Pratt bridge truss (Fig. 27).

[Short wire rods permanently inserted in the ends of the struts, *a*, slip loosely through holes in the top and bottom members, *b*; the tie-rods, *c*, are each provided with a thumbscrew at the top,

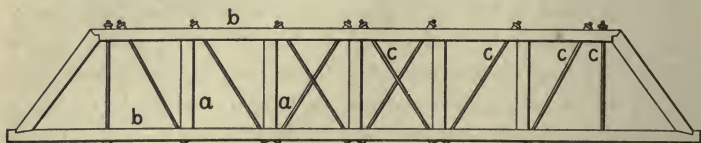


FIG. 27.

by which they are tightened. Suitable dimensions for the truss are : length 100 cm., height 15 cm., cross section of top and bottom members and struts half inch square. The tie-rods are slender rods of iron or steel ; the other members of hard wood.]

Experimental Work. — *a.* Put the truss together, and test its stiffness when the tie-rods are tight and also when they are loose. Observe whether the tension of the tie-rods increases when the truss is carrying a load. (This can be tested by noting the pitch of the sound when the rods are plucked. The greater the tension the higher the pitch.)

b. Test the stiffness of the truss when inverted, and account for the result, noting particularly the behavior of the tie-rods.

c. Observe and account for the curvature of the truss when the rods are overtightened.

d. The parts or members of the truss are the top and bottom chords, the struts (the vertical members), the end braces, and the tie-rods. Which of these are “tension members” and which are “compression members”? Which require stiffness? Account for the stiffness of the truss as a whole.

V. DYNAMICS AND MACHINES

EXERCISE 16. FALLING BODIES: WHITING'S METHOD

References. — Adams, 28-32; Colenian, 91-98; Car. & C., 33-34, 60-61; Ches. G. and T., 114-118; Hoad. Br., 39, 78-79, 81; Hoad. El., 42-43, 45; Mumper, 55-56; Mil. & G., 38-47; Went. & H., 168-171.

Experiment 34. — *To find the acceleration of a falling body.*

Apparatus. — A long stick suspended to swing as a pendulum (Fig. 28); meter rod; ball; carbon paper; thread; pins; matches; watch or small clock with seconds dial; large piece of cloth.

[For the pendulum use a stick from 1.5 to 3 m. long, of rectangular cross section about 2 by 4 cm. Suspend it by a strip of canvas or leather, with its wider side turned toward the suspended ball. A strip of carbon paper is fastened at top and bottom of the pendulum, with paper beneath to receive the impression. The ball must be heavy enough to hold the pendulum at a considerable angle, as shown in the figure; if of wood, it should not be less than about 5 cm. in diameter. For a long pendulum, an iron ball about 3 cm. in diameter may be necessary. The apparatus must be so adjusted that the suspended ball just touches the pendulum when the latter hangs vertical.]

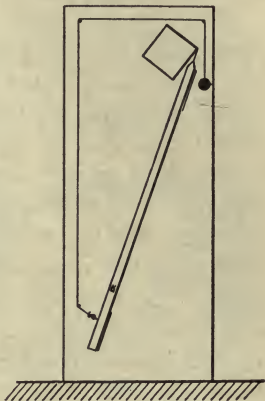


FIG. 28.

Experimental Work. — Fold the cloth into a small mat and place it on the floor so that the ball will fall on it. Place a strip of white paper under the carbon paper at top and bottom of the pendulum. This strip should be as long as the carbon paper and a centimeter or more wider than the pendulum. Fold the extra width over, make a sharp crease, open out the fold at a right angle, and fasten to the side of the pendulum with two pins (out of the way of the falling ball). Adjust the ball and pendulum as shown in the figure, by means of a thread passing over the three nails. The ball should hang near the middle of the paper. Without letting the thread slip on the nails, strike the ball against the carbon paper, marking its position by the dot thus made on the paper beneath. *Stop the swinging of the ball* (rotation, due to the untwisting of the thread, does not matter, but the results will be worthless if the ball is swinging at all), then burn the thread between the upper nails. The pendulum should strike the ball, making a dot on the lower paper. Measure the distance between the upper and lower dots.

Make a second trial; but before doing so, mark the dots already made on the paper, so they will not be mistaken for new ones. It is better to replace the paper by a new piece after a few trials. If the second result does not differ by more than 1 cm. from the first, take the average of the two. If the difference is greater than 1 cm., make further trials till you get three or more results agreeing within 1 or 2 cm., and take their average. Call the average distance s .

The ball falls s cm., while the pendulum is swinging to a vertical position, *i.e.* while it is making half a swing in one direction. To determine this time, set the pendulum swinging, and count the number of swings it makes in exactly 60 sec., timing with the second-hand of a watch. Repeat, if you are at all doubtful of the result.

Data and Computations. — The rate of the pendulum does not change as the arc through which it swings grows less; hence from the number of swings in 60 sec. you can determine the time of

one swing. Half this time is the time it takes the ball to fall s cm. Compute this time, and call it t . Substitute your values of s and t in the formula for falling bodies, and solve for g . Compute the percentage of error of your result. Record as follows:—

Distance the ball falls before striking the pendulum:

first trial = cm.; second trial = cm.; average, s = cm.

Number of swings the pendulum makes in 60 sec.:

first trial = ; second trial = ; average =

Time of $\frac{1}{2}$ swing, or time of fall of the ball, t , = sec.

Value of g from the experiment $= \frac{2s}{t^2}$ = cm.

True value of g = 980 cm.

Error =

Percentage of error = %

EXERCISE 17. FALLING BODIES: PACKARD'S METHOD

References. — Adams, 28–32, 48–51, 56–60; Coleman, 66, 91–106; Car. & C., 33–34, 48, 60–61; Ches. G. & T., 114–118, 156; Hoad. Br., 39, 78–82, 111 *a*; Hoad. El., 42–44, 91; Mumper, 55–56, 63, 81, 90; Mil. & G., 38–47, 51–52; Went. & H., 168–173.

Experiment 35. — *To find the relation between the distance passed over and the time in uniformly accelerated motion.*

Apparatus. — A broad inclined plane, with an auxiliary incline (Fig. 29); steel ball, 1 in. or more in diameter, accurately turned and polished; large sheet of carbon paper; rule.

[The plane should be at least 16 in. square, with a width of at

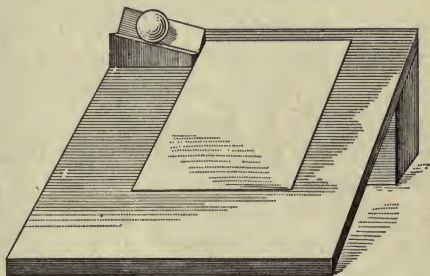


FIG. 29.

least 11 in. at the side of the auxiliary plane, and must be smooth and even. The auxiliary plane should be about 5 in. long, and provided with a groove running exactly parallel to the top and bottom of the principal plane. This groove is so constructed that the ball does not drop on passing from it to the principal plane. Both planes are inclined at an angle of about 15° . A spring clip to hold the paper in position at the top is desirable. This device for the study of accelerated motion is due to Mr. John C. Packard, of the Brookline, Mass., High School. A very complete and convenient apparatus for this experiment is manufactured by the L. E. Knott Apparatus Co., Boston.]

Experimental Work. — Place a large sheet of writing paper (not smaller than 8×10 in.) on the plane in the position shown in Figure 29. Place the ball in the groove of the auxiliary plane, and let it roll down and over the paper. Observe its path over the paper, and find by trial at what point on the auxiliary plane the ball must be released to cross the bottom of the paper near the farther corner. This is the path that the ball should describe when the record is taken.

Before taking a record, see that the edges of the sheet are exactly parallel with the edges of the plane, and that it just touches the foot of the auxiliary plane. Hold the paper in this position while taking the record, if a spring clip is not provided. Lay the carbon paper on the record sheet (with the black side down), and release the ball at the point previously determined. The ball must be freed from the control of the auxiliary plane exactly at the point where it starts across the paper (or at some other *definitely marked* point), and its path at that point must be parallel to the top edge of the paper. Be sure you have the right adjustment. Repeat till at least two satisfactory traces of the path of the ball are secured. (Use the other side of the paper for a second trace, or take another sheet.)

Take one or more traces with the paper extending lengthwise from right to left (instead of from top to bottom). In this case

start the ball higher up the auxiliary plane, so that it will cross the bottom of the sheet near the farther corner, as before.

Principle of the Method.— If any number of *equidistant* parallel lines be drawn on a sheet on which the ball has traced its path, taking for the first of these lines the edge of the paper at which the trace begins, these lines will divide the curve into parts ab' , $b'c'$, $c'd'$, $d'e'$ (Fig. 30), which were traversed by the ball in equal times. This is explained as follows: The motion along the curve may be resolved into two components at right angles to each other—one across the plane (from left to right in the figure) and the other down the plane. These we shall call the horizontal and the downward components, respectively. The horizontal component was wholly imparted on the auxiliary plane. It remains constant on the principal plane, since there is no force acting to change it (friction, being inappreciably small, is disregarded). If the principal plane were horizontal, the ball would cover the equal distances ab , bc , cd , and de in equal times, the velocity being constant. With the principal plane inclined, the direction of the unbalanced force acting on the ball is down the plane, and it affects only the downward component of the motion. Knowing, therefore, that the ball covers equal distances from right to left in equal times, whether the plane is inclined or not, it follows, as stated above, that the equidistant parallel lines divide the curved path into parts which the ball traversed in equal intervals of time. During the first of these equal time intervals the downward distance covered is bb' , during the first two intervals it is cc' , during the first three dd' , etc. This downward motion

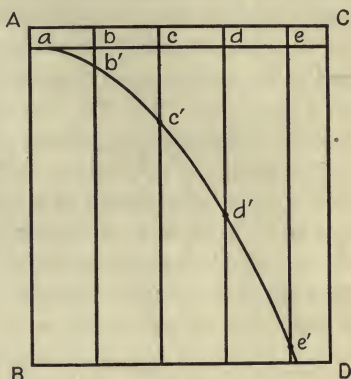


FIG. 30.

is in no wise affected by the horizontal motion — the ball would make equal progress down the plane if it had a greater horizontal component of motion or if it had no horizontal motion at all. In this experiment the horizontal component of motion merely serves the purpose of marking equal time intervals.

Construction and Comparison. — On one of your record sheets draw very accurately five equidistant parallel lines, as in Figure 30, taking the equal distances such that the fifth line cuts the curve near its lower end. The first line AB must be taken through the point where the ball passes from the control of the auxiliary plane and is free to follow a curved path. Letter the sheet to correspond with Figure 30. The five lines mark off four equal time intervals. Draw the horizontal line $abcde$. Measure accurately the downward distances bb' , cc' , dd' , and ee' . The distance ee' being the greatest, it is probably determined with the greatest accuracy. It is therefore taken as the basis of comparison. Find the difference between bb' and $\frac{1}{16} ee'$, between cc' and $\frac{4}{16} ee'$, and between dd' and $\frac{9}{16} ee'$. If the work is carefully done, these differences will not exceed 1 or 2 mm. Record as follows: —

TIME TAKEN FOR THE RESPECTIVE DISTANCES	SQUARE OF THE TIME	DOWNWARD DISTANCES		DIFFERENCE
		Measured	Computed from ee'	
1 interval	$1^2 = 1$	$bb' = \text{--- cm.}$	$1 16 ee' = \text{--- cm.}$	--- cm.
2 intervals	$2^2 = 4$	$cc' = \text{--- cm.}$	$4 16 ee' = \text{--- cm.}$	--- cm.
3 intervals	$3^2 = 9$	$dd' = \text{--- cm.}$	$9 16 ee' = \text{--- cm.}$	--- cm.
4 intervals	$4^2 = 16$	$ee' = \text{--- cm.}$	$16 16 ee' = \text{--- cm.}$	--- cm.

Make a similar construction and tabulation of results for the other curves taken, varying the work, however, by marking the curve off into three or five equal time intervals, instead of four, as above. When three intervals are taken, compare the first downward distance with $\frac{1}{9}$ of the third, and the second with $\frac{4}{9}$ of the

third ; where five intervals are taken, compare the first downward distance with $\frac{1}{2^5}$ of the fifth, the second with $\frac{4}{2^5}$ of it, the third with $\frac{9}{2^5}$ of it, and the fourth with $\frac{16}{2^5}$ of it.

Preserve and hand in the sheets on which the curves were taken and the constructions made, as a part of the record of the experiment.

Discussion (oral except the first question). — 1. What relation does this experiment establish (within a small limit of error) between the downward distance and the time? Derive this relation from the tabulated record.

2. How is it known that the horizontal component of the motion of the ball is constant?

3. What is the unbalanced force acting on the ball when it is on the principal plane? What is its direction? Is it a constant or a variable force? Prove your answer.

4. What is the direction of the acceleration of the ball? Why? Is it a constant or a variable acceleration? How is this shown by the results? What is the reason for its being so?

EXERCISE 18. THE SIMPLE PENDULUM

References. — Adams, 76–78, 81–82 ; Coleman, 130–135 ; Car. & C., 68–71 ; Ches. G. & T., 164–166 ; Hoad. Br., 83–85 ; Hoad. El., 92–95 ; Mumper, 95 ; Mil. & G., 224 ; Went. & H., 189–191.

Apparatus. — A pendulum stand with three pendulums of adjustable length, one with wooden and two with iron or lead bobs (Fig. 31) ; watch or clock with second-hand ; meter rod.

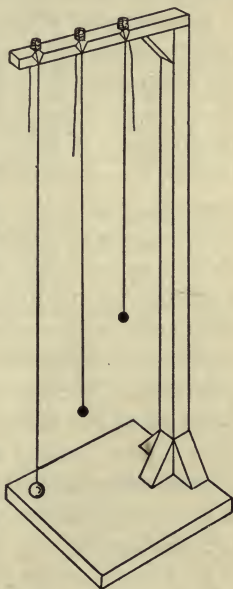


FIG. 31.

[A convenient and efficient adjustable suspension is shown in Figure 31. A slanting notch is cut at an angle of about 35° to



FIG. 32.

receive the thread, and a cork glued above, in which is cut a slit to receive the thread. The friction in the cork holds the pendulum. The pendulum clamp shown in Figure 32 is also especially adapted to the requirements of the exercise. It can be clamped to any support rod.]

Experiment 36. *To find whether the amplitude of a pendulum affects its rate.*

Experimental Work. — *a.* Adjust the two pendulums with iron bobs to exactly the same length, making them about as long as the apparatus will permit. Test the equality of their lengths by careful measurement, and also by starting them together with equal amplitudes. If there is even a very slight difference in their lengths, the shorter will slowly gain on the other, and the difference will begin to be noticeable in a minute or so.

After securing exact adjustment, start the pendulums together, giving one an amplitude of not more than 5° and the other an amplitude of 30° to 35° . Observe whether the pendulums continue for at least a minute to begin and end their swings together. A difference as small as a tenth of a swing can be *seen*, whereas a difference of one whole swing is the least that would be detected by counting the number of swings made by each pendulum in a given time. Do not count, but observe. Verify the result by a second trial, giving the larger amplitude to the other pendulum. About what difference, if any, do you observe in the rates of the two pendulums?

b. Again start the pendulums together, giving one an amplitude of about 6° and the other less than 3° . Let them swing thus for a minute or more. How do their rates compare?

c. What do the above tests show concerning the effect of the amplitude of a pendulum on its rate?

Experiment 37.— *To find whether the rate of a pendulum is affected by either its mass or its material.*

Experimental Work.— Adjust the pendulum with a wooden bob to the same length as one with an iron bob. The pendulums should be long. The length is measured from the point of support to the middle of the bob. Start the two pendulums together, with equal amplitudes (not above 10°), and observe whether one gains on the other in a minute or more. How do you find the rates of the pendulums to be affected by the fact that they are of unequal mass and of different materials?

Experiment 38.— *To find the relation between the period of a pendulum and its length.*

Experimental Work.— Adjust the three pendulums to lengths having the ratio of 1, $\frac{1}{4}$, and $\frac{1}{9}$. Lengths of 36 in., 9 in., and 4 in. will be most convenient, if the height of the support will permit. Count the number of single vibrations that each of the pendulums makes in exactly 60 sec.

If you have time, test the ratio of the periods of the pendulums by starting together the 36-in. and the 9-in. pendulums, and observe how many swings of the shorter occur during one swing of the longer. Test the 36-in. and the 4-in. pendulums in the same way.

Data and Computations.— Let l denote the length of a pendulum and t the time of one vibration. Compute for each of the pendulums the value of the ratio $\sqrt{l}:t$ (to be expressed decimally). Record in tabular form, as follows:—

LENGTH = l	WHOLE TIME	NO. OF SWINGS	TIME OF 1 VIBRATION = t	$\sqrt{l}$	$\sqrt{l}:t$
36 in.	60 sec.	—	—	—	—
9 in.	60 sec.	—	—	—	—
4 in.	60 sec.	—	—	—	—

Discussion. — 1. If there were no errors, the value of the ratio $\sqrt{l}:t$ would be the same for the three pendulums. Compute the percentage of difference between the greatest and the least of these values. This should not exceed 2 %.

2. What is the probable source of the greatest error in the experiment?

3. From the equal values of the ratio $\sqrt{l}:t$ for all pendulums, derive the proportion between the lengths of any two pendulums, l_1 and l_2 , and their periods, t_1 and t_2 .

EXERCISE 19. THE WHEEL AND AXLE

References. — Adams, 100-103, 112-113; Coleman, 159-161, 168-169; Car. & C., 89-92, 96-97; Ches. G. & T., 143-144, 147; Hoad. Br., 93-94, 104-105; Hoad. El., 101-105, 113-114; Mumper, 83-85, 89; Mil. & G., 207, 212-213; Went. & H., 206-211.

Definitions. — In this and the following exercises on machines, the same kind of quantity is always represented by the same letter. The definitions of these quantities and the letters by which they are represented are as follows:—

The body moved by a machine is called the *load*. The resisting force that the load exerts while being moved is called the *resistance*, and it is denoted by R . In these laboratory exercises the machine is used to raise the load; in which case the work is done against gravity, and the resistance R is the weight of the load.

The body that does the work, or supplies the energy for raising the load, is called the *agent*. The force that the agent must exert to maintain equilibrium, or the force that would be required to do the work if there were no friction, is called the *static effort*, and is denoted by E_s . The force that the agent must exert to move the load is necessarily greater than E_s . It is called the *working effort*, and is denoted by E_w . In these laboratory exercises the agent consists of one or more standard masses (weights),

and their united weight constitutes the static effort E_s , or the working effort E_w , according to whether it maintains equilibrium or raises the load.

The distance through which the effort (or the agent) acts is called the *effort distance*, and is denoted by D_e ; and the vertical distance through which the resistance is overcome (or the load is raised) is called the *resistance distance*, and is denoted by D_r .

According to the rule for the measure of work (see text), *the work done by the working effort* (or the agent) is denoted by $E_w D_e$, and *the work done against the resistance* (or upon the load) is denoted by $R D_r$. In other words, $E_w D_e$ denotes the energy transferred from the agent to the machine, and $R D_r$ denotes the energy transferred from the machine to the load.

The *efficiency* of a machine is defined as the ratio of the work done on the load (the *useful work*) to the total energy expended by the agent; *i.e.*

$$\text{Efficiency} = \frac{R D_r}{E_w D_e}.$$

Experiment 39.—*To find the mechanical advantage and the efficiency of a wheel and axle.*

Apparatus.—Mounted axle carrying two wheels of different diameters, with cords attached and a hook at the end of each cord; meter rod; set of weights running to 500 g. or, better, to 1000 g.

[The “universal laboratory weights” shown in Figure 21 are recommended as most convenient for all experiments with machines. An ordinary set of weights can be used by tying a loop of stout thread to each, by which they can be hung on hooks attached to the ends of the cords. It is more convenient, however, to tie a small bucket or pan to the cord to hold the weights. If the set runs to 1000 g., weights smaller than 10 g. are unnecessary; if the largest is 500 g., 5 g. is the smallest required. Weights are more accurate and are better in other respects for determining the effort than the draw scale.]

Experimental Work.—*a.* Hang one or more of the largest weights (the load) on the cord attached to the axle; and hang just sufficient weights (the agent) on the cord attached to one of the wheels to raise the load slowly (Fig. 33). If a bucket or pan for holding these weights is attached to the cord, its weight must be included as part of the effort. It will probably be found that, on account of varying friction, the motion is not uniform; but, on the average, the motion should neither be accelerated nor retarded. Record the weight of the load R , and the effort with the load rising. The latter is the *working effort* E_w .

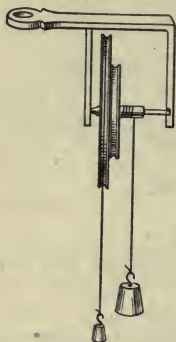


FIG. 33.

Find the effort required to maintain steady motion as the load slowly descends. (Reduce the effort by removing weights, but leave the load unchanged.) The average of these two values of the effort is the *static effort* E_s . (Why?)

Measure the distance D_e through which the effort acts (the distance that the agent descends) and the distance D_r through which the load is raised, when the load is raised from the lowest to the highest point that the adjustment of the apparatus will permit. (It will be found most convenient and most accurate to measure all

distances from the level of the table or the level of the floor, according to the position of the apparatus. For example, the height of the load above the floor at the start subtracted from its height above the floor after it has been raised, gives the distance D_r .)

Measure the diameters of the wheel and the axle. (If it is inconvenient to measure these diameters directly, measure the length of the cord that goes just once around the circumference, and divide this length by 3.1416.)

b. If time permits, repeat the experiment, using the axle and the other wheel or the two wheels, regarding the smaller one as the axle in the latter case.

Data and Computations.—Record as follows:—

	<i>a</i>	<i>b</i>
Weight of the load <i>R</i>	— g.	— g.
Effort with load rising, or working effort <i>E_w</i>	— g.	— g.
Effort with load descending	— g.	— g.
Distance through which effort acts, <i>D_e</i> .	— cm.	— cm.
Distance through which load is raised, <i>D_r</i>	— cm.	— cm.
Radius of wheel <i>A_e</i> (arm of the effort) .	— cm.	— cm.
Radius of axle <i>A_r</i> (arm of resistance) .	— cm.	— cm.

COMPUTATIONS

Average or static effort <i>E_s</i>	— g.	— g.
Mechanical advantage (by definition) = $R \div E_s$	—	—
Mechanical advantage (from the dimensions of the machine) = $A_e \div A_r$	—	—
Work done on the load = RD_r	— g.-cm.	— g.-cm.
Work done by the agent = $E_w D_e$	— g.-cm.	— g.-cm.
Efficiency of the machine = $RD_r \div E_w D_e$.	— %	— %

Discussion. — 1. Show from the principle of moments of force that the ratios $R : E_s$ and $A_e : A_r$ should be equal. (The effort and the resistance tend to turn the wheel and axle in opposite directions.) Which of these ratios determines what the value of the other must be for a given wheel and axle?

2. It can be proved geometrically that $D_e : D_r :: A_e : A_r$. (Prove it.) Compare your experimental values for these ratios.

3. From the proportions given in the first two questions, show that $R : E_s :: D_e : D_r$ or $E_s D_e = RD_r$. It follows that,

$$\text{Efficiency} = \frac{RD_r}{E_w D_e} = \frac{E_s D_e}{E_w D_e} = \frac{E_s}{E_w};$$

that is, the efficiency is equal to the ratio of the static effort to the working effort. Compute the efficiency from this ratio, and compare the result with the value obtained from $RD_r \div E_w D_e$.

4. Prove that the mechanical advantage of the wheel and axle is equal to the ratio $D_e : D_r$. State this relation in words.

EXERCISE 20. PULLEYS

References. — Adams, 115–116; Coleman, 162–165, 168–169; Car. & C., 98–100; Ches. G. & T., 148–155; Hoad. Br., 107–110; Hoad. El., 116–119; Mumper, 88; Mil. & G., 204–207; Went. & H., 212.

Apparatus. — A single and two double or triple pulleys; frame with screw hooks to support the pulleys (Fig. 34); meter rod; stout, flexible cord (heavy fishing-line); set of weights to 1000 g.; small hook or a weight bucket, if the weights are not provided with hooks.

Experiment 40. — *To find the mechanical advantage and the efficiency of a single fixed pulley.*

Experimental Work. — Suspend a pulley (a single one, if provided), and pass a cord over it. Fasten the largest weight (the load) to one end of the cord. Tie a loop in the cord on the other side of the pulley, at a convenient height (attach the weight bucket or a hook to the loop, if the weights have no hooks), and hang just sufficient weights in it to raise the load slowly and steadily. (If the remaining weights of the set are not sufficient for this, use a smaller weight for the load.) Record the weight of the load R , and the working effort E_w (the effort with the load rising).

Find the effort required to maintain steady motion as the load slowly descends. (Reduce the effort by removing weights, but leave the load unchanged.) The average of these two values of the effort is the static effort E_s . (Why?)

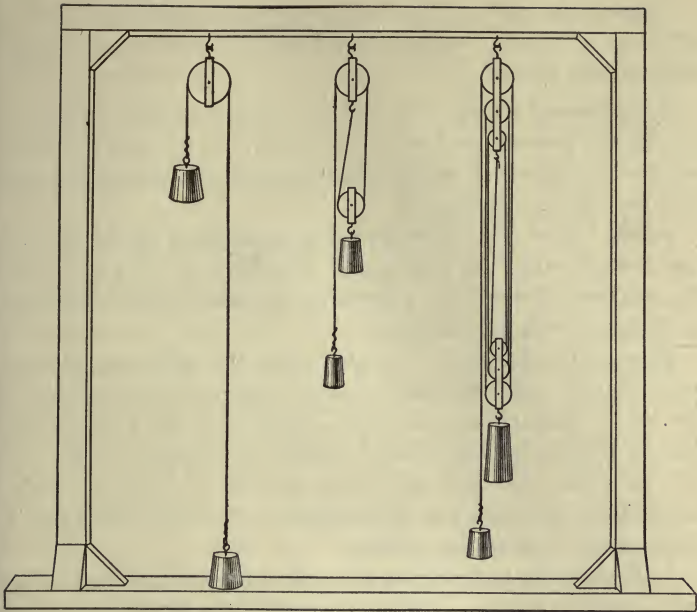


FIG. 34.

Data and Computations. — As in the case of the wheel and axle, it can be shown that the efficiency of the fixed pulley is equal to the ratio of the static effort E_s to the working effort E_w . Take this ratio as the measure of the efficiency. Record as follows:—

Weight of the load R	=	g.
Effort with load rising, or working effort, E_w	=	g.
Effort with load descending	=	g.
Average or static effort, E_s	=	g.
Experimental value of mechanical advantage $= R \div E_s$	=	
True value of mechanical advantage (= number of parts of the cord supporting the load)	=	1
Percentage of error	=	%
Efficiency of the fixed pulley $= E_s \div E_w$	=	%

Experiment 41.— *To find the mechanical advantage and the efficiency of a single movable pulley and of a combination of fixed and movable pulleys.*

Experimental Work.— *a.* When a movable pulley is used, it becomes a part of the load to be raised. Weigh every movable pulley used (unless its weight is recorded on it), and add its weight as a part of the resistance R .

Adjust a fixed and a movable pulley as shown in Figure 34. Use the 1000-g. weight (or the largest provided) as the load. Find the working effort and the effort with the load slowly descending, as in the preceding experiment.

Measure the distance D_e through which the effort acts (the distance that the agent descends) and the distance D_r through which the load is raised when the load is raised from the lowest to the highest convenient point (which should be at least 25 cm.). (It will be most convenient and most accurate to measure all distances from the bottom of the support, or from the table top, if that is directly under the pulleys.)

b. Repeat the experiment, using two or three fixed and two or more movable pulleys. Use two or more of the heaviest weights for the load, and remember to include the weight of the movable pulleys as a part of the resistance R . Make a drawing of the arrangement of pulleys used.

Data and Computations.— Record measurements and computations as follows:—

	<i>a</i>	<i>b</i>
Weight of the load (including weight of movable pulleys) R	— g.	— g.
Effort with load rising (working effort), E_w .	— g.	— g.
Effort with load descending	— g.	— g.
Distance through which effort acts, D_e . .	— cm.	— cm.
Distance through which load is raised, D_r .	— cm.	— cm.

COMPUTATIONS

	<i>a</i>	<i>b</i>
Average or static effort, E_s	— g.	— g.
Experimental value of mechanical advantage $= R \div E_s$	—	—
True value of mechanical advantage (number of parts of cord supporting load) . . .	2	—
Percentage of error of mechanical advantage .	— %	— %
Work done on the load $= RD_r$	— g.-cm.	— g.-cm.
Work done by the agent $= E_w D_e$	— g.-cm.	— g.-cm.
Efficiency, computed from $RD_r \div E_w D_e$.	— %	— %
Efficiency, computed from $E_s \div E_w$	— %	— %

Discussion (Oral). — 1. By definition, the efficiency of a machine is $RD_r \div E_w D_e$. Prove that this is equal to $E_s \div E_w$ (*a*) for a single fixed pulley, (*b*) for a single movable pulley, (*c*) for any combination of fixed and movable pulleys.

2. Prove that the mechanical advantage of any combination of pulleys is equal to the ratio $D_e : D_r$.

EXERCISE 21. THE INCLINED PLANE

References. — Adams, 58, 118; Coleman, 166–169; Car. & C., 101–102; Ches. G. & T., 156; Hoad. Br., 111; Hoad. El., 120; Mumper, 90; Mil. & G., 214; Went. & H., 46.

Experiment 42. — *To find the mechanical advantage and the efficiency of an inclined plane.*

Apparatus. — An inclined plane, with single fixed pulley at top (Fig. 35); roller or car, with its weight marked on it; metric rule; set of weights.

Experimental Work. — *a.* Set the plane at an angle of about 25° . (The angle need not be measured.) Place the roller or car on the plane, pass a cord from it over the pulley, and attach just sufficient weights to the cord to draw the roller (or car) slowly and steadily up the plane (Fig. 35). (If a car and weights to

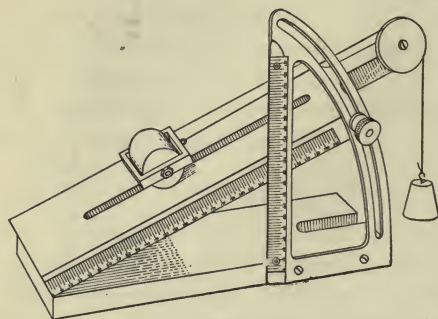


FIG. 35.

1000 g. are provided, more accurate results will be obtained by loading the car with one or more of the heavier weights.) Record the weight of the load R , and the working effort E_w .

Find the effort required to maintain steady motion as the load rolls slowly down the plane.

Measure the length L of the plane along its under edge, from its lower end to the straight, vertical edge of the support. Measure the height H of the plane at the vertical edge of the support, from the under edge of the plane to the upper edge of the base.

b. Repeat the experiment with the plane at an angle of about 45° .

Data and Computations. — Record as follows : —

	<i>a</i>	<i>b</i>
Weight of the load R	— g.	— g.
Effort with the load rising (working effort), E_w	— g.	— g.
Effort with load descending	— g.	— g.
Length of the plane L	— cm.	— cm.
Height of the plane H	— cm.	— cm.

COMPUTATIONS

	<i>a</i>	<i>b</i>
Average or static effort E_s	— g.	— g.
Mechanical advantage, from $R \div E_s$. .	—	—
Mechanical advantage, from $L \div H$. .	—	—
Percentage of difference	— %	— %
Work done on the load in rolling it up the plane = RH	— g.-cm.	— g.-cm.
Work done by the agent = $E_w L$	— g.-cm.	— g.-cm.
Efficiency, computed from $RH \div E_w L$. .	— %	— %
Efficiency, computed from $E_s \div E_w$. . .	— %	— %

Discussion (Oral). — Taking $RH \div E_w L$ as the definition of the efficiency of the inclined plane, prove it to be equal to $E_s \div E_w$.

EXERCISE 22. GEARED WHEELS

(INVENTIVE)

Experiment 43. — *To find the mechanical advantage and the efficiency of a train of geared wheels.*

Apparatus. — Set of geared wheels (Fig. 36), mounted on a suitable support, with a cord to support the load and a stout thread to support the agent; weights to 1000 g.; meter rod.

Suggestion. — The pupil is left to work out the details of this experiment and the form

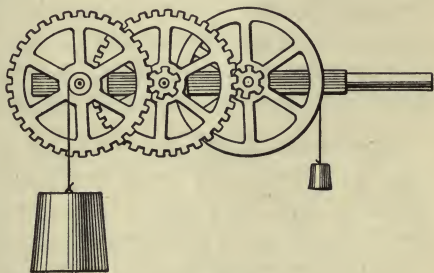


FIG. 36.

of record for himself. The mechanical advantage can be found experimentally by three independent methods, and the efficiency by two. Employ any or all of these that occur to you.

VI. MOLECULAR PHENOMENA

EXERCISE 23. COHESION AND ADHESION

References. — Adams, 126-132; Coleman, 188-193; Car. & C., 17-18; Ches. G. & T., 62; Hoad. Br., 28; Hoad. El., 31, 130; Mumper, 22; Mil. & G., 157-159; Went. & H., 142, 144, 146.

Experiment 44. — *To study the effect of distance on molecular attraction, and to study the behavior of liquids in contact with solids.*

Apparatus. — Two pieces of plate glass and two of window glass, each about 6 cm. square; piece of glass coated with paraffine; bottle containing a little mercury; sealed bottle containing clean mercury and very small pieces of glass; vessel of water; dropping tube; mop cloth.

[The pieces of glass should be between 2 mm. and 4 mm. in diameter, and there should be just enough mercury in the bottle to cover about one third of the bottom. The surface of the mercury must be clean and bright. Sealing the bottle with wax will preserve the mercury from other use, and keep it clean.]

Experimental Work. — *a.* Have the pieces of plate glass clean and dry. Press them firmly together, then note the force required to pull them apart. Is cohesion between them great enough to lift one of them by means of the other?

b. Try the two pieces of window glass in the same way. How do the results compare with the preceding? The surfaces of the plate glass are quite accurately plane, while those of the window glass are more or less uneven and wavy. The difference in the results in the two cases is due to this difference in the surfaces.

Hence the experiments illustrate a necessary condition for the existence of cohesion. What is this condition?

c. Again take the pieces of plate glass, dip them in water to moisten their surfaces, and press them together as before. Note the force now required to pull them apart. How does it compare with the force required when the plates are dry? The thin layer of water adheres to the glass surface on each side, forming a connecting link.

Is adhesion between water and glass stronger or weaker than cohesion within a piece of glass? How is this shown? Why is adhesion between water and glass stronger than cohesion between the two pieces of plate glass? Is cohesion in water stronger or weaker than adhesion between water and glass? How is this shown?

d. CAUTION. In handling mercury, be careful not to get any of it on jewelry. It unites with gold and silver, forming an amalgam which discolours the surface.

By means of the dropping tube transfer a small drop of mercury from the bottle to a piece of glass. Flatten the drop with the finger, then observe the effect of removing the finger. The behavior of the drop does not prove that there is no adhesion between mercury and glass. What does it prove? Why does the drop of mercury not flatten out and spread over the glass as a drop of water would?

With the finger or the point of your pencil, detach a very small bit from the drop. Is this smaller portion more or less nearly spherical than the larger portion? Why? Pour the drop of mercury into your hand and return it to the bottle.

e. Take the sealed bottle containing mercury and bits of glass. Incline it slightly from side to side so that the mercury will run about over the bottom of the bottle, and note the behavior of the bits of glass toward the mercury. What evidence of adhesion between glass and mercury do you observe?

f. Observe the behavior of a drop of water on the paraffined surface of the piece of glass. Do you find cohesion within water

stronger or weaker than adhesion between water and paraffine? Do you infer that adhesion between water and paraffine is greater or less than between water and glass?

EXERCISE 24. SURFACE TENSION AND CAPILLARITY

References.—Adams, 150-156; Coleman, 195-200; Car. & C., 113-122; Ches. G. & T., 63-65; Hoad. Br., 119-126; Hoad. El., 130-136; Mumper, 23-25; Mil. & G., 160-167; Went. & H., 145, 147.

Experiment 45.—*To study various phenomena due to surface tension.*

Apparatus.—Tumbler of clean water; pins; two small slivers of wood (toothpicks); very slender rubber band; lifter made of wire, for placing pins on water (Fig. 37); small bottle of alcohol; glass rod; dish of soap solution; wire ring about 3 in. in diameter, with extension of wire for handle, and with thread tied loosely across the ring (Fig. 38); bottle containing a drop of oil suspended in a solution of alcohol and water of its own density.

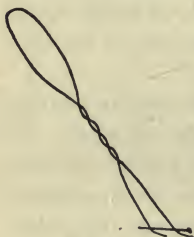


FIG. 37.

[For a good soap solution, put 2 oz. of Castile soap, shaved thin, in 1 pt. of distilled or rain water. Shake, pour off the clear solution, and add to it $\frac{1}{2}$ pt. glycerine, and stir. To prepare the suspended drop of oil, pour a very little water into the bottle and add an equal or greater quantity of alcohol without shaking. This will leave the mixture somewhat denser at the bottom. Insert 2 or 3 large drops of olive or machine oil by means of a dropping tube. Slowly pour in more alcohol, if necessary, till the drop sinks below the surface.]

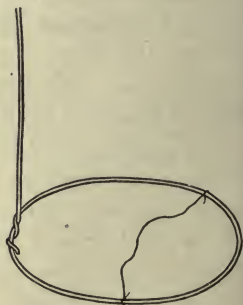


FIG. 38.

Experimental Work. — *a.* Place a pin on the lifter (Fig. 37), and lower it gently till the pin floats on the water, then remove the lifter. If the pin sinks now or later in the experiment, take it out with the lifter, wipe it dry with the fingers (which leaves it somewhat oily), and try again. Observe closely the shape of the water about the pin. Describe it, and draw an enlarged figure of a cross section of the pin and adjacent water surface, taken at right angles to the length of the pin.

Push the pin till it breaks through the surface. Why does it sink now? Why did it float before?

b. Float two wooden toothpicks on the water, placing them parallel and about 2 cm. apart. (Pins can be used, but it is difficult to keep them afloat.) Dip the glass rod into the alcohol, and carry a drop on the end of it to the surface of the water between the toothpicks. What happens? The alcohol, mixing with the water between the toothpicks, weakens the surface tension. How does this account for the behavior of the toothpicks?

Repeat the experiment, using the rubber band instead of the toothpicks, and drop the alcohol inside the band.

Similar results would be obtained if oil were used in these experiments, instead of alcohol; but it would be necessary to change the water after each trial. Why?

c. Dip the wire ring into the soap solution, and withdraw it obliquely. Repeat if necessary, till a film is obtained. Observe the behavior of the loose thread as it floats in the film. With the point of a pencil, break the film on one side of the thread. Describe and account for the behavior of the thread. Draw a figure showing the position it takes with a film on only one side of it.

d. What is the shape of the oil globule suspended in the mixture of alcohol and water? What gives it this shape? Disturb the drop by tipping the bottle slightly from side to side, but not so quickly as to break the drop. When the drop is distorted by this motion, does it recover its former shape? Account for this behavior.

Experiment 46. *To study capillary action with reference to the effect of the size of the tubes and the direction of the curvature of the liquid.*

Apparatus. — Capillary tubes of glass of different sizes ; capillary tubes coated inside with paraffine ; glass of water ; glass containing mercury.

[To coat a tube with paraffine, put a very small piece of paraffine in one end of the tube, and hold it obliquely in a flame till the paraffine melts and runs down the tube.]

Experimental Work. — *a.* Observe the shape of the water and mercury surfaces near the glass. Draw figures of vertical sections through the liquids, to illustrate. Account for the difference in the shape of the two surfaces.

b. In the following work use one set of capillary tubes in water only and the other set in mercury only. Place tubes of different sizes in the tumbler of water. Make a section drawing of the tumbler and tubes, showing the height of the water and the shape of its surface in the tumbler and in the tubes. How does the diameter of a tube affect the height to which water rises in it above the level in the tumbler? How is the water raised and sustained in the tubes?

c. Repeat the preceding with tubes of different sizes in mercury, using only dry tubes. By pressing the tube against the side of the tumbler an unobstructed view of the inside of the tube will be obtained. Describe what is seen and make a section drawing to illustrate.

d. Place in the tumbler of water the capillary tube coated on the inside with paraffine. Is the water in the tube elevated above or depressed below the level of the water in the tumbler? Is the surface of the water in the tube convex or concave?

Discussion. — Is the liquid in a capillary tube elevated or depressed when the surface of the liquid is concave? when the surface is convex? State the reason in each case.

VII. HEAT

EXERCISE 25. CONDUCTION AND CONVECTION

References. — Adams, 374-379; Coleman, 215-218; Car. & C., 343-349; Ches. G. & T., 213-216; Hoad. Br., 253-256; Hoad. El., 271-276; Mumper, 140-142; Mil. & G., 291-297; Went. & H., 115-120.

Experiment 47.—*To determine the order in which glass and different metals stand as conductors of heat.*

Apparatus.—Rods of brass, iron, copper, and glass (about No. 9 or 10 wire); Bunsen burner; vessel of water; test tube.

Experimental Work.—Test the relative conductivity of the rods, two at a time, holding one in each hand, with an end of each in the Bunsen flame 6 or 8 cm. above the burner, the two being as nearly as possible equally heated. At first hold the rods near the heated end; then, as they became uncomfortably hot, hold them farther from this end, observing in which the heat travels faster. The method may be varied by holding the rods at the same distance from the heated end, and observing in which the heat first reaches the hand.

Before trying the same rod a second time, it may be cooled in the vessel of water, except the glass rod, which must be allowed to cool of itself, for it will break if thrust into the water hot. Continue experimenting till you can arrange the rods in the order of their conductivity.¹ Write the names in order, from the best to the poorest conductor.

¹ The rise of temperature along the rods depends upon another property of the substances besides their conductivity. This property, called specific heat, will be studied later. It does not affect the order of conductivity of the materials used in this experiment.

b. Fill the test tube with water within 2 or 3 cm. of the top. Hold it at the bottom in the fingers, tipping it slightly, and apply the Bunsen flame a little below the top of the water (Fig. 39), till it boils at the top for about a minute.

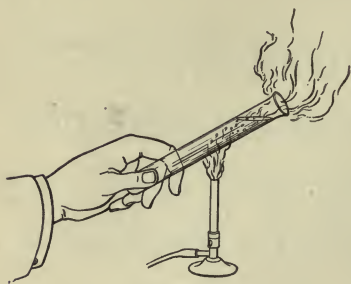


FIG. 39.

What do you observe concerning the temperature of the water at the bottom of the tube? What do you conclude concerning the conductivity of water?

Experiment 48. *To observe whether sensations of heat and cold are affected by the conductivity of the substances touched.*

Apparatus. — Two pieces each of several of the following substances : brass, iron, glass, copper, wool, asbestos, stone, and wood ; hot air bath ; ice box (unless the weather is cold).

Experimental Work. — *a.* Place one set of the substances in the air bath and apply a low flame for several minutes. Place the other set in the ice box, or, if the weather is cold, in the open air outside a window. After five minutes or more, when all the substances in the bath have had time enough to come to the same temperature (the temperature of the bath), grasp them in the hand, one at a time, without removing them from the oven, and note the temperature sensation. Repeat until you can write a list of them in order, beginning with the one that *feels* the hottest. (It is incorrect to say that one *is* hotter than another.) Note the temperature sensation due to the hot air of the bath, and include air in the list of substances. Account for the *seeming* difference of temperatures.

b. Try the same substances cooled in the ice box or outside the window, and arrange a list in order, beginning with the one that feels the coldest. In making this test it is better to press

the substances, two at a time, against the forehead, which is much more sensitive than the hands. After testing any substance it must be allowed to cool again before making a further test of it. Account for the seeming difference of temperatures.

Experiment 49. — *To study convection currents in water.*

Apparatus. — Test tube; Bunsen burner; beaker; sawdust; iron stand; wire gauze; mop cloth.

Experimental Work. — *a.* Put a small pinch of sawdust in the beaker, and fill it nearly full of water. Wipe the outside of the beaker dry, place it on the wire gauze on the ring stand, and apply heat with the Bunsen flame. The gauze should be about 10 cm. above the burner, and the flame turned down so that it will not burn above the gauze. Observe carefully the motion of the particles of sawdust while the water is heating. Give a full account of what is observed, including definite reasons for any motion of the liquid that you may infer from the behavior of the sawdust.

b. Fill the test tube nearly full of water and hold it in the hand just below the surface of the water, and apply the flame near the bottom. Note the rapidity of the rise of temperature of the water at the top.

Compare with the experiment in conduction, in which the heat was applied near the top of the tube and the tube was held near the bottom. Account for the difference in the results of the two experiments.

EXERCISE 26. RADIANT ENERGY

References. — Adams, 381-385; Coleman, 219-226; Car. & C., 350, 352-354; Ches. G. & T., 217; Hoad. Br., 258-263; Hoad. El., 280-286; Mumper, 146-151; Mil. & G., 299-300; Went. & H., 121-125.

Experiment 50. — *To study the transmission, absorption, and reflection of radiant energy.*

Apparatus. — Bunsen burner; a bright tin screen about 8 by 8 in., mounted on stand or supported by ring stand and clamp;

mounted tin screen, same size, painted black or coated with soot on one side.

Experimental Work. — *a.* Hold the hand in different positions near the flame, at the side and above it. Do you feel convection currents in any position? There may possibly be convection currents that are too weak to be felt as currents, although they warm the hand. Can you suggest any conclusive reason for believing that the hand is not warmed by such a current when held at the side of the flame?

b. Hold the hand close beside the flame, and note the intensity of the sensation. With the hand still in this position, insert a sheet of paper between it and the flame, and note the effect on the sensation of heat. How does this effect prove that the hand was not heated by conduction through the air from the flame?

c. Place the tin screens on opposite sides of the flame, at equal distances of about 10 cm. from it, with the black side of the one turned toward the flame. After a minute or two, note the temperature of the screens by placing a hand flat against each on the side turned from the flame. What do you learn concerning the temperatures of the two screens? How is this explained?

d. Remove the bright screen and hold one hand in its place at the same distance from the flame as the other hand, which is still pressed against the back of the black screen. Which hand becomes warmer? Explain.

e. What facts point to the conclusion that the black screen becomes much hotter than the air at that distance from the flame? Why is this?

Experiment 51. — *To find whether radiant energy is transmitted along a straight path, and to test the power of different substances to absorb and transmit luminous and non-luminous radiation.*

Apparatus. — Bunsen burner; radiometer; three flat bottles of clear glass, one empty, one filled with water, and one with a solution of iodine in carbon bisulphide.

CAUTION. Carbon bisulphide is dangerously inflammable. The bottle must be kept tightly corked and must be handled with care. It should be provided with a support to avoid danger of overturning.

Experimental Work. — *a.* Place the radiometer at different distances from the flame, and observe the effect of distance upon the rate of rotation of the vanes. Radiation, both luminous and non-luminous, falling upon the radiometer, will cause the vanes to rotate; and the rate of rotation is an indication of the intensity of the radiation.

b. Place the radiometer about 30 cm. from the flame and slowly insert a sheet of paper or a book between them. What is the position of the screen when the slower rotation of the vanes indicates that the radiation has been cut off from the radiometer? Does the effect of the screen indicate that radiant energy is or is not transmitted along a straight path?

c. Hold the empty flask between the flame and the radiometer, and bring the latter up till the vanes make about one rotation per second. Now remove the flask and note the effect on the radiometer. What do you infer in regard to the power of clear glass to absorb radiant energy?

d. Without moving the radiometer or the flame, hold the flask of water between them. Compare the result with that obtained with the empty flask. A more definite comparison may be made by observing the time of, say, ten rotations; but where there are easily observable differences, this is not necessary.

Is water a good or poor absorber of luminous radiation? (Is it transparent?) Does the action of the radiometer show that water is a good or poor absorber of non-luminous radiation? (Probably more than 95 % of the energy radiated from the flame is of the non-luminous variety.)

e. Substitute the flask containing the solution of iodine in carbon bisulphide. Compare the results with the preceding. Does the solution transmit light (luminous radiation)? What evidence

is there that it transmits non-luminous radiation? Is it a better or poorer transmitter of non-luminous radiation than water? better or poorer than glass?

EXERCISE 27. COEFFICIENT OF LINEAR EXPANSION

References. — Adams, 351; Coleman, 233; Car. & C., 319; Ches. G. & T., 220-221; Hoad. Br., 264-265; Hoad. El., 287-288; Mumper, 113-114; Mil. & G., 197; Went. & H., 96.

Experiment 52. — *To find the expansion of 1 cm. of a brass rod due to a rise of temperature of 1° .*

Apparatus. — Linear expansion apparatus (Fig. 40); apparatus for generating steam; tumbler; meter rod; Bunsen burner; access to a thermometer.

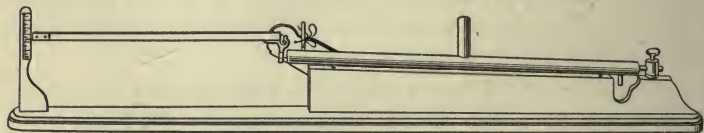


FIG. 40.

[For the steam generator use a copper boiler on tripod, with a tight top, or flask with stopper and delivery tube, supported on a ring stand.]

Experimental Work. — *a.* Fill the steam generator from one third to one half full of water, and with the top off (or the delivery tube disconnected at the generator) begin heating it. While the water is heating, measure the length of the brass rod without removing it from the steam jacket; then adjust it so that one end rests against the fixed support and the other against the lever. Turn it so that the escape tube will be directed downward. Set the tumbler under this tube to catch the escaping steam and hot water.

b. Read to .1 mm. the position of the long lever arm on the vertical scale. After taking this reading, be careful not to disturb

the apparatus in any way, as this would probably move the lever into a new position.

c. The temperature of the rod is the same as that of the room. Find it by the laboratory thermometer.

d. Put the top on the steam generator and connect the delivery tube. While the rod is being heated by the steam, observe the motion of the long lever arm. After the steam has been escaping freely from the escape tube for two or three minutes and no further motion of the lever can be detected, read the position of the long lever arm. The temperature of the rod is the same as the temperature of the steam, which may be assumed to be 100° .

e. Measure the arms of the lever. These are the distances from the fulcrum (a knife edge or the center of a screw) to the scale and from the fulcrum to the point of contact with the brass rod, respectively. When you have finished, tilt the apparatus so that the water condensed in the steam jacket will run out.

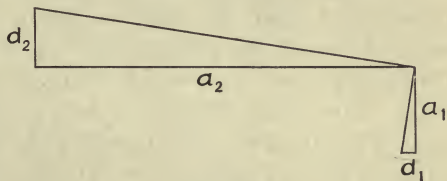


FIG. 41.

Data and Computations.—The whole expansion of the rod is the distance d_1 (Fig. 41) that the short arm

of the lever is pushed forward. Compute this from the proportion $d_1 : d_2 :: a_1 : a_2$. Record data and computations as follows:—

MEASUREMENTS

Length of brass rod	=	cm.
First position of long lever arm	=	cm.
First temperature of the rod	=	$^{\circ}$ C.
Final temperature of the rod	=	$^{\circ}$ C.
Final position of long lever arm	=	cm.
Length of long lever arm a_2	=	cm.
Length of short lever arm a_1	=	cm.

COMPUTATIONS

Rise of pointer on the index, d_2	=	cm.
Change of temperature of the rod	=	° C.
Expansion of rod for this change of temperature, d_1	=	cm.
Expansion of rod for 1° change of temperature	=	cm.
Expansion of 1 cm. of rod for 1° change of temperature (coefficient of linear expansion of rod)	=	cm.
True value of coefficient of expansion of brass	=	.0000188
Percentage of error	=	%

ALTERNATIVE DIRECTIONS

If the apparatus is provided with a micrometer screw instead of a lever, the following substitutions are to be made in the directions as given above :—

b. If you do not know how to read the micrometer screw, turn it back and forth and study its action. Note the fixed millimeter scale and the circular scale on the head ; also that when the head is turned once round, it advances 1 mm. along the fixed scale. How many divisions are there on the circular scale ? The value of one division on the circular scale is the distance the screw advances when the head is turned through one division. What is this value ? Ask for assistance if necessary. The answers to these questions need not be recorded.

See that the other end of the rod is against the fixed support, then turn the micrometer screw till it just touches the rod, and take its reading. *After taking the reading, turn the screw back 2 or 3 mm. to make room for the expansion of the rod when heated.* If this precaution is not observed, the expanding rod will strain and damage the apparatus. Observe the additional precautions given in paragraph *b* above.

d. In this paragraph substitute for the reading of the lever a second reading of the screw, after it has been turned up to touch the rod. The difference between the two readings of the screw is the expansion of the rod.

EXERCISE 28. COEFFICIENT OF EXPANSION OF AIR

References.—Adams, 352–353; Coleman, 237; Car. & C., 318–320; Ches. G. & T., 223; Hoad. Br., 268–269; Hoad. El., 293–295; Mumper, 118; Mil. & G., 191; Went. & H., 97.

Experiment 53.—*To find whether the expansion of air is uniform, and to find by what fraction of its volume at 0° air expands when its temperature is raised 1° .*

Apparatus.—Copper steam generator with tall top; Bunsen burner; hydrometer jar; stirrer of wire bent into a flat coil at the end; thermometer; glass tube containing air and mercury index; metric rule; ice.

[The tube containing air must be of small bore (not greater than 1 mm.), in order to hold the mercury index in position, and should be 35 to 40 cm. long. Prepare as follows: Thoroughly dry the tube by warming it and passing through it air that has first passed through a calcium chloride drying tube. Insert an end of the tube into clean mercury, withdraw a column about 2 cm. long, and let it run some distance down the tube. Seal an end of the tube in a flame, then work the index into proper position with a fine wire, leaving the confined air column about two thirds the length of the tube.]

Method.—The thread of mercury in the glass tube serves as an air-tight piston to confine a fixed mass of air between it and the closed end of the tube.

Since the tube is of uniform bore, the volume of this confined air is proportional to its length. This length is determined when the tube is surrounded by melting ice, when it is immersed in warm water, and when immersed in steam. The tube is in each case vertical, with the open end up, when the measurements are taken; hence the confined air is under a constant pressure (the pressure of the atmosphere plus the pressure due to the weight of the mercury index).

Experimental Work.—Handle the tube carefully; a sudden motion might break the thread of mercury, and this must be avoided. Measure accurately the total length of the bore of the tube (*i.e.* the distance from the open end to the inside of the closed end), and the length of the mercury index.

Place the tube, open end up, in the hydrometer jar, and fill the jar with crushed ice or snow up to the index. While waiting a minute or two for the tube to come to the temperature of the ice, fill the steam generator about two thirds full of water and begin heating it. With the tube still in the ice, tap it *very lightly* to jar the index into its true position, then measure the distance from the top of the index to the top of the tube. Subtracting this distance, together with the length of the mercury index, from the total length of the bore of the tube gives the length of the confined air column. Its length at the other temperatures is found in the same way.

Remove the tube, pour the water from the jar, and return the remaining ice to the supply vessel. Fill the jar with water from the faucet, and let it stand a moment to warm the jar, then empty and fill with water at 35° to 40° from the supply that is being heated. *Be careful not to pour hot water into the jar; if thick glass is heated suddenly, it will break.* Stir the water in the jar thoroughly by moving the stirrer repeatedly from top to bottom of the jar; place the tube and thermometer in it; take the temperature accurately; and after tapping the tube lightly, measure the distance from the top of the index to the top of the tube.

Place the top on the steam generator, and boil the water. Push the tube through the hole in the cork which closes the top of the generator, and push it farther down as the index rises in the tube, until finally the index appears just above the cork when it has become stationary. After the steam has been escaping from the vent for some time and the index has ceased to rise, measure the distance from the top of the index to the top of the tube.

Leave the tube standing in the empty hydrometer jar.

Data and Computations. — Record data as follows, and perform the indicated computations : —

MEASUREMENTS

Total length of bore of tube	=	cm.
Length of mercury index	=	cm.
Distance from top of index to top (open end) of tube		
when tube is in ice (temp. 0° C.)	=	cm.
when tube is in water at ---° C. (This temperature is denoted below by t°)	=	cm.
when tube is in steam (temp. 100°)	=	cm.

COMPUTATIONS

Length of air column at 0°	=	cm.
Length of air column at t° (temp. in water)	=	cm.
Length of air column at 100°	=	cm.
Average expansion of air column per degree rise of temperature		
between 0° and t°	=	cm.
between t° and 100°	=	cm.
between 0° and 100°	=	cm.
Computed coefficient of expansion between 0° and 100°	=	cm.
True value of coefficient of expansion of air	=	.00366
Percentage of error	=	%

Discussion. — What information do your results afford on the question whether the expansion of air is uniform within the temperature limits of the experiment?

EXERCISE 29. SPECIFIC HEAT

References. — Adams, 369, 371-373; Coleman, 239-243; Car. & C., 325-328; Ches. G. & T., 226-230; Hoad. Br., 281-283; Hoad. El., 312-314, 316; Mumper, 110-112; Mil. & G., 239, 250-251; Went. & H., 107-109.

Experiment 54. — *To find the number of calories required to raise the temperature of 1 g. of ——— 1°.*

Apparatus. — Bunsen burner ; copper vessel on tripod, or other open vessel for boiling water ; open roll (Fig. 42) or other mass of metal, with fine wire attached for handle ; calorimeter ; thermometer ; platform balance and weights to 500 g. ; mop cloth.

[The piece of metal whose specific heat is to be found should weigh from 250 to 400 g. A sphere or other compact mass will serve ; but an open roll of sheet metal 1 to 2 mm. thick is

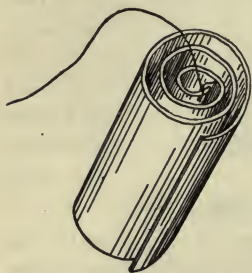


FIG. 42.

better. The space between the surfaces of the roll must be wide enough to avoid holding water by capillary action. A light calorimeter of thin nickel-plated brass or of aluminum is preferable ; but a glass beaker or even a small tin can will serve. It makes a rather better experiment to find the specific heat of the metal of which the calorimeter is made, using a roll or other mass of the same metal.]

Experimental Work. — Begin heating water in the copper boiler. Weigh the piece of metal whose specific heat is to be found.

Weigh the calorimeter. Put the roll into the calorimeter, and pour in enough water to cover it. The water should be about 3° below the temperature of the room, for best results. Put the roll into the water that is being heated, and see that there is enough water in the boiler to cover it. Weigh the calorimeter and the water in it.

After the above has been done and the water in the vessel is boiling, thoroughly stir the water in the calorimeter with the thermometer and take its temperature to a tenth of a degree. (The temperature must be read as accurately as possible. An error of .1° in determining a temperature change of 5° is an error of 5 %.)

As soon as the temperature is taken, remove the thermometer, hold the calorimeter close beside the boiler, and transfer the roll

to the calorimeter as quickly as possible. (It is assumed that the temperature of the roll is 100° when it is put into the calorimeter ; but it cools with great rapidity during the transfer, and a delay of even a second will cause a considerable error in the result.) Place the calorimeter on the table at a distance from the flame, move the roll about in it to stir the water, then insert the thermometer and take the temperature near the top and the bottom of the water and on opposite sides of the roll. If differences are found, stir again. Record the highest uniform temperature.

If time permits, the experiment should be repeated. Having become familiar with the method of procedure, you will very probably secure better results. Leave the calorimeter empty.

Data and Computations. — Let s denote the specific heat of the roll. If the calorimeter is of the same metal as the roll, its specific heat is also denoted by s . That is, s denotes the number of calories lost by each gram of the roll as its temperature falls one degree, and also the number of calories received by each gram of the calorimeter as its temperature rises one degree. If the calorimeter and the roll are of different metals, the specific heat of the calorimeter is treated as a known quantity in the computations, and its value is taken from a table of specific heats.

The calorimeter is assumed to be at the temperature of its contents. The heat gained by the water and the calorimeter is assumed to come entirely from the roll (any transfer of heat between the vessel and outside bodies is disregarded) ; *i.e.*

$$\begin{aligned} \text{Heat lost by roll} &= \text{heat received by water} \\ &+ \text{heat received by calorimeter.} \end{aligned}$$

The algebraic statement of this relation (*i.e.* with the quantities expressed numerically or algebraically) is called *the heat equation*. The specific heat is found by solving this equation for s .

Be careful to specify in the record what metal is used in the experiment and of what metal the calorimeter is made. Record as follows : —

Weight of roll of —	=	g.
Weight of — calorimeter	=	g.
Weight of calorimeter and water	=	g.
Initial temperature of water and calorimeter	=	° C.
Initial temperature of roll of —	=	100° C.
Final temperature of calorimeter and contents	=	° C.

COMPUTATIONS

Weight of water used	=	g.
Rise of temperature of water and calorimeter	=	°
Heat received by water	=	cal.
Heat received by calorimeter = () × () × s	=	cal.
Fall of temperature of roll	=	°
Heat given out by roll = () × () × s	=	cal.
Heat equation and its solution: —		
Computed specific heat of —, s	=	
True value of the specific heat	=	
Percentage of error	=	%

EXERCISE 30. MELTING AND FREEZING

References. — Adams, 386–388 ; Coleman, 231, 244–247 ; Car. & C., 311, 329–332 ; Ches. G. & T., 207, 232–237 ; Hoad. Br., 240, 271–273 ; Hoad. El., 257, 298–300 ; Mumper, 105, 122–123 ; Mil. & G., 180, 264–269, 273 ; Went. & H., 94, 99–101.

Apparatus. — Thermometer, numbered for identification ; tumbler or beaker ; test tube ; supply of ice and salt.

Experiment 55. — *To find the error of the zero point on a thermometer scale.*

Experimental Work. — *a.* Fill the beaker about half full of fine crushed ice. Insert the thermometer, and pack the ice about it nearly to the zero of the scale. After the mercury ceases to fall, take the temperature to .1°. Record the number of the thermometer and its reading in melting ice. The graduation of thermometers, except expensive ones, may be in error by several

tenths of a degree. The temperature of melting ice (when by itself) is exactly zero. The reading of a centigrade thermometer in melting ice is therefore the error of its zero point.

b. What evidence is there that the ice you used was melting? Was the ice receiving or losing heat during the experiment? How and why?

Experiment 56.— *To find whether freezing and melting take place at the same temperature.*

Experimental Work.— *a.* Mix with the ice in the beaker about one fourth its volume of table salt. Put enough water into the test tube to cover the bulb of the thermometer when inserted in it, and place it in the freezing mixture of salt and ice. Stir the water in the test tube with the thermometer, keeping watch of its temperature. At what temperature does it begin to freeze? Continue the stirring and take the temperature from time to time as the freezing continues. What is the reading of the thermometer in freezing water? How do the temperatures of melting ice and freezing water compare?

b. After a third or a half of the water in the tube is frozen, allow the remainder to freeze round the bulb of the thermometer. What change of temperature do you observe after the water is all frozen?

To free the thermometer from the ice, let water from the faucet run on the test tube. Take the temperature of the freezing mixture. Was the water in the test tube receiving or losing heat while it was freezing? Why?

Experiment 57.— *To observe the effect of pressure upon the melting point of ice.*

Apparatus.— A block of ice supported at the ends; a heavy weight suspended from the block of ice by means of a loop of fine wire passed over it.

[The most convenient procedure with this experiment is for the teacher to set it up, at or just before the beginning of the laboratory period, and have all the members of the class observe its progress from time to time during the hour.]

Experimental Work. — *a.* When the weight was hung upon the ice, the wire rested upon its surface. How do you find it now? Look at it from time to time during the hour, and note any change in the position of the wire.

b. How is the cut that the wire makes in the ice mended? What is the cause of the melting under the wire? What is the source of the heat required for this melting? Why does the water above the wire freeze? (Heat received by the ice from the air and other bodies does not reach the interior.)

EXERCISE 31. HEAT OF FUSION AND SOLUTION

References. — Adams, 389-392; Coleman, 248-250; Car. & C., 332-334; Ches. G. & T., 238-240; Hoad. Br., 284; Hoad. El., 315; Mumper, 124-125; Mil. & G., 264-265, 281; Went. & H., 110-111.

Experiment 58. — *To find the number of calories required to change 1 g. of ice at 0° into water at 0°.*

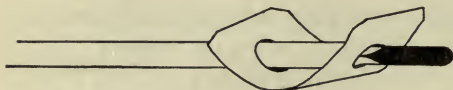


FIG. 43.

Apparatus. — Calorimeter; thermometer and stirrer (Fig. 43); platform balance and weights to 500 g.;

cloth; ice plane; supply of ice and of hot water.

[For a stirrer use a piece of very thin sheet copper about 1×1.5 in., with two holes large enough to slip it on the end of the thermometer.]

Experimental Work. — Weigh the calorimeter to .1 g. Put into it about 150 g. of water at a temperature between 45° and 50°. Take hot water from the supply and add cold water till the temperature is right. Weigh the calorimeter and water. During the remainder of the experiment the calorimeter should stand on wood or paper (poor conductors), and should be touched by the hands as little as possible.

Have at hand a quantity of shaved or crushed ice. *This must be dry.* (Why?) It is best prepared by shaving it with an ice plane immediately before using it. The quantity required will have a volume about equal to the volume of water used. If a supply of crushed ice is provided, dry it as much as possible by spreading it out on a cloth and wiping each piece with a corner of the cloth.

Thoroughly stir the water in the calorimeter with the stirrer on the thermometer, and take the temperature to $.1^{\circ}$. Immediately put in nearly all of the ice, and stir the water constantly while the ice is melting. If ice remains after the temperature has fallen to about 8° , remove it with the stirrer; if the ice is all melted before the temperature has fallen to 10° or 12° , add more without delay. As soon as the temperature has fallen to about 8° and no ice remains in the calorimeter, stir the water thoroughly and take the temperature at top and bottom. If there is a difference, stir and read again. Record the lowest uniform temperature of the water.

Weigh the calorimeter and contents. Leave the calorimeter empty, and the table dry.

Data and Computations.—The experiment is planned so that the heat lost from the calorimeter and contents by radiation and conduction while they are warmer than the air is approximately balanced by the heat gained by the same means after they have become colder than the air. We may therefore assume that the heat received by the ice in melting and the heat received by the ice water in warming to the final temperature comes entirely from the warm water and the calorimeter, and that the heat received by the ice and the ice water is equal to the heat lost by the warm water and the calorimeter. Let f denote the heat of fusion of ice (the number of calories required to melt one gram of ice without change of temperature). Take the specific heat of the calorimeter from the table of specific heats in the Appendix. Write the heat equation and solve it for f . Record data and computations as follows:—

Weight of the calorimeter	=	g.
Weight of calorimeter and water	=	g.
Temperature of calorimeter and water just before adding ice	=	° C.
Final temperature of calorimeter and water	=	° C.
Final weight of calorimeter and water (including water from the ice)	=	g.

COMPUTATIONS

Weight of water before adding ice	=	g.
Weight of ice added	=	g.
Fall of temperature of calorimeter and water	=	°
Heat given out by warm water	=	cal.
Heat given out by calorimeter	=	cal.
Heat received by the ice in melting = () $\times f$	=	cal.
Heat received by the ice water in warming to the final temperature	=	cal.
Heat equation and its solution : —		
Computed heat of fusion of ice, f	=	cal.
True value of heat of fusion of ice	=	79.25 cal.
Percentage of error	=	%

Experiment 59. — *To observe the change of temperature when ammonium chloride or ammonium nitrate is dissolved in water.*

Apparatus. — Thermometer ; test tube ; ammonium chloride or ammonium nitrate.

Experimental Work. — Fill the test tube about one third full of water and take its temperature. Add a teaspoonful or more of ammonium chloride or ammonium nitrate, stir with the thermometer, and note the change of temperature. What inference may be drawn from this change of temperature?

If there is time, repeat the experiment with ice-water. Compare the fall of temperature in the two cases, and note particularly whether the temperature falls below the freezing point of pure water.

EXERCISE 32. COOLING BY EVAPORATION; DEW-POINT

References. — Adams, 393, 397, 401-403; Coleman, 251-252, 256-259; Car. & C., 335-336, 339, 341; Ches. G. & T., 243-249; Hoad. Br., 274-276; Hoad. El., 302-305; Mumper, 126-127, 134-136; Mil. & G., 133-143, 145-146; Went. & H., 102-103, 113, 127-128.

Experiment 60. — *To compare the rate of evaporation of water, alcohol, and ether, and to observe the change of temperature due to evaporation.*

Apparatus. — Small bottles containing water, alcohol, and ether; thermometer; absorbent cotton.

Experimental Work. — *a.* Pour a few drops of water on the palm of the hand, and move the hand back and forth edgewise. Note the temperature sensation and the rapidity with which the water evaporates. Try the same experiment with alcohol.

Compare the rapidity of evaporation of water and alcohol and the temperature sensations. Account for the difference in the temperatures.

b. Repeat the experiment, using ether. Compare results with those obtained with water and alcohol. Account for the difference in the temperatures.

c. Take the temperature of the air. Wrap a small quantity of cotton round the bulb of the thermometer, and insert it in the bottle of water. Take the temperature of the water. Raise the bulb out of the water, but leave it still inside the bottle, and after about half a minute take the temperature. Remove the thermometer from the bottle, and observe any change in the reading as it is held in the air for a short time. After the temperature has become constant, move the thermometer to and fro several times, and again read the temperature. Record the observed temperatures on separate lines.

Account for the equality of or the difference between the various temperatures.

d. Replace the cotton on the bulb of the thermometer with a dry piece, and repeat the preceding experiment, using ether instead of water.

Compare the results with those obtained with water. Why does the temperature cease to fall before all the ether has evaporated from the cotton?

Experiment 61.—*To find the dew-point of the air in the laboratory.*

Apparatus.—Thermometer; stirrer of thin copper; bright calorimeter; two beakers; ice.

Experimental Work.—*a.* Put water in the calorimeter to a depth of about three centimeters. Have at hand a beaker of water, and a small quantity of shaved or finely crushed ice in the other beaker. Add ice to the calorimeter, *a very little at a time*, stirring constantly with the stirrer on the thermometer. Watch closely meanwhile for the first deposit of moisture on the calorimeter near the bottom; and when it appears, take the temperature of the water. It is the *highest* temperature at which moisture is deposited that is to be found. If the moisture gathers quickly and abundantly, the water is too cold. If this happens, add warmer water to the calorimeter, wipe the outside dry, and repeat, being careful to cool the water more gradually. Avoid breathing on the calorimeter. (Why?) If the dew-point is below zero, it will be necessary to add salt with the ice. If in the course of the experiment the calorimeter becomes more than half full, pour out part of the contents.

b. Starting with a *thin* film of moisture on the calorimeter, stir the water constantly till the moisture disappears, then take the temperature. The temperatures at which the dew appears and disappears should not differ by more than 1° . Take their average as the dew-point of the air in the laboratory at the time of the experiment.

EXERCISE 33. PHENOMENA OF BOILING

References. — Adams, 393-395 ; Coleman, 261-262 ; Car. & C., 337 ; Ches. G. & T., 251-254 ; Hoad. Br., 277 ; Hoad. El., 306 ; Mumper, 128-129 ; Mil. & G., 278-280 ; Went. & H., 104.

Apparatus. — Thermometer, numbered for identification ; ring stand, ring and clamp ; wire gauze ; large flask, and stopper to fit, with two holes ; delivery tube (Fig. 44) ; hydrometer jar ; Bunsen burner ; closed-tube pressure gauge containing water in the closed tube above the mercury (Fig. 45).

[To make the pressure gauge, take a

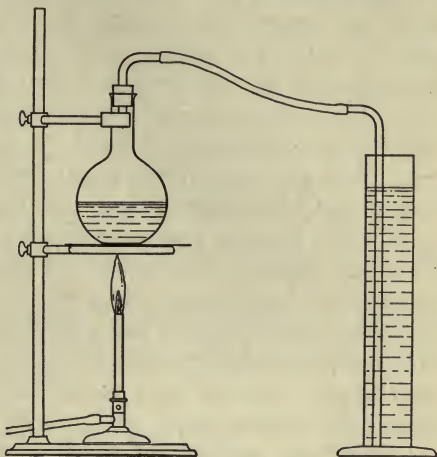


FIG. 44.

piece of small glass tubing about a foot long ; seal one end, and bend about 3 in. from the closed end, as shown in Figure 45, making the bend narrow enough to pass through the neck of the flask. A slight bend in the open arm of the tube, at right angles to the two arms, as shown in the figure, will keep the mercury from running out when the tube is laid on the table. Pour in enough mercury to fill the short arm and extend just past the bend. By holding the tube horizontal, with the closed end below, and inclining it first in one direction then in the other, the air can be gradually displaced from the closed end by the mercury. Next pour in water to a depth of about half an inch, and work a little of it into the closed arm by inclining the tube with the closed arm above.]



FIG. 45.

Experiment 62.— *To observe the phenomena preceding and accompanying boiling; and to find the temperature of the boiling water and the steam.*

Experimental Work.— Fill the flask about half full of fresh water (not water that has been boiled), wipe the outside dry, place it on the wire gauze on the stand, and apply heat. The flame must not be high enough to burn above the gauze. While the water is heating, conduct simultaneously the observations called for in paragraphs *a*, *b*, and *c*.

a. Place the thermometer in the flask, letting it rest on the bottom, and occasionally observe the temperature. Observe the water while heating, and note the first formation of bubbles. These are bubbles of air which was dissolved in the water and which is now being driven off by the heat. Describe their size, abundance, and behavior; and state through what range of temperature (approximately) they continue to be given off. (The "flat" taste of boiled water is due to the fact that it contains little or no dissolved air.)

b. Note any gathering of moisture on the inside of the flask and on the thermometer. Does it occur before the water boils? How do you account for it?

c. Note the temperature when sounds begin to come from the flask. What is their cause? Is the water boiling when the sounds begin? Watch closely for the first formation of bubbles larger than the air bubbles first observed. What are they? Where are they formed? What becomes of them? Note the temperature. Watch closely for any change in the phenomena as the temperature approaches 100° .

d. Regulate the flame so that the water boils slowly, and record its temperature. Record its temperature when it is boiling rapidly.

e. Raise the thermometer till the bulb is just out of the water. Take the temperature as accurately as possible and record it as the temperature of the steam.

Experiment 63. — *To find the vapor pressure of steam at the boiling point.*

Experimental Work. — The closed-tube pressure gauge (Fig. 45) contains water in the closed arm above the mercury. If there is a bubble at the top of the closed tube, it is air, and must be removed. Have this done by the instructor. Lower the gauge into the steam above the boiling water in the flask, and note the formation of water vapor in the closed arm. How do the levels of the mercury in the two arms compare? What does this prove concerning the relative values of the atmospheric pressure and the pressure of the water vapor in the closed arm? Observe the effect of removing the gauge from the flask. Explain.

Conclusions. — State the conclusions to be drawn from the experiment.

Experiment 64. — *To observe the effect of increase of pressure upon the boiling point; and to find the correction for the boiling point on the thermometer used.*

Experimental Work. — Remove the burner from under the flask while you are making the following adjustment. Push the thermometer through the hole in the stopper till the bulb is but little above the water when the stopper is in the flask. Be careful; if you have difficulty, call for assistance. Press the stopper firmly into the flask. Connect the delivery tube as shown in Figure 44, and let it extend to the bottom of the hydrometer jar, which should be nearly full of water. Boil the water in the flask, and take the temperature of the steam while it is escaping into the bottom of the jar of water. (The noise of the condensing steam can be greatly reduced by standing the jar on a book.) Gradually raise the delivery tube out of the jar while observing the effect upon the temperature of the steam. Raise and lower the tube till you are sure of the effect. Take the temperature while the steam is escaping into the air. Empty the flask and return the thermometer to its case.

Read the barometer.

Discussion. — 1. Discuss the experiment as an illustration of the effect of pressure on the temperature at which water boils.

2. At a pressure of one atmosphere (76 cm.) the true value of the boiling point is 100° . For pressures either slightly greater or less than one atmosphere, the temperature of steam from boiling water varies $.37^{\circ}$ for a change of pressure of 1 cm. Compute the true value of the temperature of steam at the observed barometric pressure.

3. What is the error of the boiling point on this thermometer?

EXERCISE 34. HEAT OF VAPORIZATION OF WATER

References. — Adams, 396 ; Coleman, 266-267 ; Car. & C., 342 ; Ches. G. & T., 245, 255 ; Hoad. Br., 285-286 ; Hoad. El., 317-318 ; Mumper, 133 ; Mil. & G., 275-277 ; Went. & H., 112.

Experiment 65. — *To find the number of calories given out by 1 g. of steam at 100° in condensing to water at 100° .*

Apparatus. — Flask or other steam-generating apparatus, with rubber tube and condensation trap (Fig. 46) or side-neck test tube ; Bunsen burner ; calorimeter ; thermometer and stirrer ; platform balance and weights ; ice ; mop cloth.

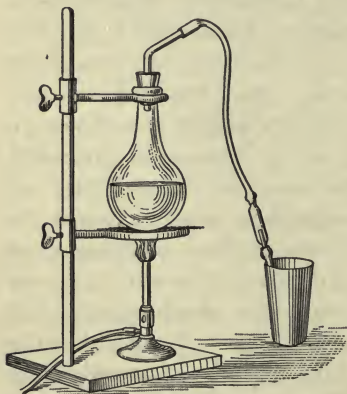


FIG. 46.

Experimental Work. — Fill the steam generator about half full of water, and begin heating it. Connect the delivery tube and condensation trap. Support the delivery tube on some object so that the escaping steam will not damage the table.

Weigh the calorimeter to .1 g. (It is especially important in this experiment that the weighing be carefully done.) Fill the

calorimeter about two thirds full of water at 0° to 5° . Add ice to water from the faucet till the required temperature is obtained. (If ice is not provided, use the coldest water obtainable.) Weigh the calorimeter and water, and remove at once from the balance.

Place the stirrer on the thermometer, and as soon as the steam is escaping freely from the delivery tube, stir the water in the calorimeter and take the temperature. Wipe off any dew that has gathered on the calorimeter, and immediately place the delivery tube in the water to a depth of an inch or two. The calorimeter should be at some distance from the burner and protected from its radiation by a screen. Stand your note book between them for this purpose. There should be no considerable loss of steam on account of poorly adjusted apparatus. If the steam is delivered properly, the temperature will rise rapidly. Stir the water constantly, keeping the hands off the calorimeter. The condensation trap must not overflow and admit hot water into the calorimeter. To empty it, remove the burner from under the boiler and lift the delivery tube till the water in the trap runs back into the boiler.

When the temperature has risen to about 40° , turn off the gas, remove the delivery tube from the calorimeter immediately, stir the water thoroughly, and take the temperature as quickly as possible.

Weigh the calorimeter and contents. Leave the calorimeter empty and the table dry.

Data and Computations. — The temperatures in the experiment are so chosen that the heat received from outside bodies while the calorimeter and water are colder than the air is as nearly as possible equal to the heat gained after they have become warmer than the air. Hence the heat gained by the water and calorimeter is assumed to come only from the steam, first in condensing to water at 100° , second in cooling to the final temperature. Let v denote the heat of vaporization of water (the number of calories given out by one gram of steam in condensing to water at 100°). Write

the heat equation, and solve it for v . Record data and computations as follows:—

Weight of calorimeter	=	g.
Weight of calorimeter and water	=	g.
Temperature of calorimeter and water just before adding steam	=	°
Final temperature of calorimeter and water	=	°
Final weight of calorimeter and water (including water from steam)	=	g.

COMPUTATIONS

Weight of water before adding steam	=	g.
Weight of steam added	=	g.
Rise of temperature of calorimeter and water	=	°
Heat received by the calorimeter	=	cal.
Heat received by the water	=	cal.
Heat given out by the steam in condensing to water at $100^{\circ} = () \times v$	=	cal.
Heat given out by water from condensed steam in cooling to final temperature	=	cal
Heat equation and its solution:—		
Computed heat of vaporization of water, v	=	cal.
True value of heat of vaporization of water	=	536 cal.
Percentage of error	=	%

EXERCISE 35. THE STEAM ENGINE

(INVENTIVE)

References. — Adams, 362–368 ; Coleman, 275–276 ; Car. & C., 357 ; Ches. G. & T., 257–260 ; Hoad. Br., 289 ; Hoad. El., 321–322 ; Mumper, 156 ; Mil. & G., 252–258 ; Went. & H., 230–233.

Experiment 66. — *To study the mechanism of a steam engine.*

Apparatus. — Section model of a steam engine (Fig. 47).

Suggestions. — Study the model in connection with the text and reference books. Describe the points illustrated by the model, referring to lettered diagrams of its various parts. A model like that shown in the figure is provided with the reversing gear used on locomotives. The reversing gear is operated by means of the lever. Find the direction in which the driving wheel of the actual engine represented by the model would turn when the lever is in the extreme front and back positions. What would be the effect of placing the lever midway between these positions? Study the effect of setting the lever part way forward and part way back. In discussing the reversing gear, refer to lettered diagrams of it.

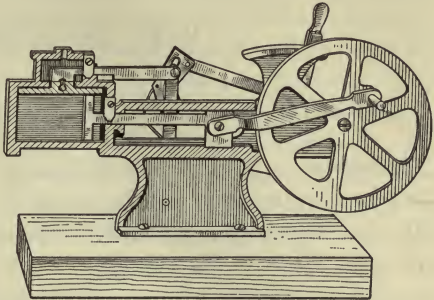


FIG. 47.

VIII. SOUND

EXERCISE 36. THE TRANSMISSION OF SOUND

References. — Adams, 208; Coleman, 277-280, 290; Car. & C., 174-179, 198-199; Ches. G. & T., 167-170; Hoad. Br., 181-184; Hoad. El., 195-198; Mumper, 162-165; Mil. & G., 444-445; Went. & H., 333-334.

Experiment 67. — *To study the transmission of sound through solids.*

Apparatus. — Meter rod; large tuning fork; rubber mallet for striking the fork; cord four or five feet long.

[For a rubber mallet bore a half-inch hole in a large rubber stopper, and insert a stick about 10 in. long for a handle; or slip a short piece of large, thick rubber tubing on the end of a stick.]

Experimental Work. — *a.* To set a tuning fork in vibration, hold it by the stem in one hand and strike one of the prongs a sharp, quick blow near its end, in the direction of the other prong. (Touching a prong of a sounding fork immediately stops it.) Hold one end of the meter rod close to the ear while your companion holds the stem of the vibrating fork against the other end of the rod. Note the loudness of the sound. Listen to the sound of the fork through the air at the same distance, the rod being removed. Compare the loudness of the sound transmitted through the rod and through the air.

b. Hold an end of the rod between your teeth while the stem of the sounding fork is held against the other end. The sound travels through the rod, the teeth, and the bones of the head to the ear. Describe the result. Do you feel the vibrations?

c. Hold the stem of the vibrating fork against the teeth ; against the top of the head. State the result.

d. Tie a string one or two meters long to the stem of the fork. Press one end of the string into your ear, while your companion sets the fork vibrating and holds it so as to stretch the string moderately tight. Try the effect of slackening the string ; also the effect of removing it from the ear when tightly stretched. What have you learned about the transmission of sound by the string ?

e. Touch the stem of the vibrating fork to the table top. The loud sound comes from the table, which is set in vibration by the fork. Hold an end of the meter rod against the side of the table, and the vibrating fork against the other end of the rod. State and account for the result.

f. Place the rubber stopper of the mallet between the vibrating fork and the table. How does the stopper compare with the rod in its power to transmit sound ? To what is the difference due ?

Experiment 68.— *To study the construction and use of an acoustic telephone line.*

Apparatus.— An acoustic telephone line, with stations at opposite ends of the laboratory or in adjacent rooms ; tuning fork ; mallet.

[To make an acoustic telephone, make a small hole in the middle of the bottom of two small tin cans or chalk boxes, fasten them up at some distance apart, and stretch a cord or small copper wire rather tightly between them, fastening the ends to some small object, as a button, on the inside of the bottom of the cans. The cord must not be supported by fastening it rigidly to any object. It may be supported at any point by a short cord, and may be carried round a corner by giving it three or four such supports at the corner, making each bend slight. The acoustic telephones supplied by dealers are more satisfactory.]

Experimental Work.— Listen at one end of the telephone line, while your companion places the stem of a vibrating fork against

the telephone at the other end. Try speaking to each other through the telephones.

Note the construction of the telephones and the manner in which the connecting wire (or cord) is supported. Describe the various details observed, and explain their purpose.

Experiment 69.— *To find whether water transmits sound.*

Apparatus.— Battery jar of water; large tuning fork; large cork or small block of wood with hole to fit the stem of the fork; rubber mallet.

Experimental Work.— Place a jar of water on the table. Insert the stem of the fork into the hole in the cork (or block). Set the fork in vibration and hold it with the cork immersed in the water, but not touching the glass. Raise the cork out of the water and again immerse it, repeating the process a number of times, and note the effect on the loudness of the sound. State the result.

With the fork sounding and its stem in the water, try the effect of lifting the jar from the table and again replacing it. Does the sound come principally from the jar of water or from the table when the jar stands on the table?

How does the experiment answer the question whether water transmits sound?

Experiment 70.— *To study the transmission of sound through a speaking tube.*

Apparatus.— A tin or large glass tube 6 ft. to 10 ft. long; roll of cotton or soft cloth; watch.

Experimental Work.— Lay a watch on a roll of cotton or soft cloth (to prevent the transmission of the sound through the table) at one end of the tube, and listen at the other end to the sound of the ticking. About how near to the watch must you hold the ear to hear it as distinctly directly through the air as through the tube?

Explain the effect of the tube.

EXERCISES 37. RIPPLES. REFLECTION OF SOUND

References. — Adams, 195-196, 213; Coleman, 281-283, 293; Car. & C., 164-165, 167, 169-172, 184-186; Ches. G. & T., 170-173, 181; Hoad. Br., 185-188, 193-195; Hoad. El., 200-203, 209-211; Mumper, 157-160, 165, 167; Mil. & G., 448-455, 459-460; Went. & H., 334-338, 340-341.

Experiment 71. — *To study the origin, transmission, and reflection of ripples.*

Apparatus. — Ripple trough, strip of tin about 2 in. wide and about the width of the trough, bent into an arc of about 70° ; thin board about 3 in. wide and a trifle shorter than the width of the trough.

[The ripple trough is a shallow box with a glass bottom. For the sides use 1.5×2.5 in. wood or larger, and for the bottom a window pane not smaller than 20×24 in., — larger, up to 24×30 in., is preferable. Plate glass gives a uniform depth of water, which is very desirable. The wooden sides should be given two or three coats of boiled oil or a coat of hot paraffine to prevent absorption of water. An inch hole should be bored in one end and closed with a cork, for convenience in emptying the trough.]

Experimental Work. — *a. Origin and propagation of waves.* — Spread a large sheet of white or very light colored paper on a table near a window where the light is strong, and place the trough on the paper. This arrangement makes the ripples distinctly visible. Fill the trough with water to a depth of about 1 cm. Start a wave at the center of the trough by dipping the finger into the trough and quickly removing it. Observe the shape of the wave and the direction or directions in which it travels. Repeat till sure of the results. Describe what is observed.

b. Start a series or train of waves by tapping rapidly with the finger at the center of the trough. Describe the appearance of the train of waves and their behavior.

c. Place the board on edge in the trough in the position shown at *ab* (Fig. 48). With a slight forward and backward motion of

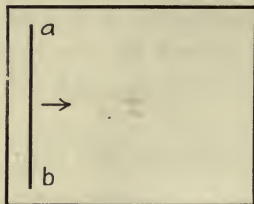


FIG. 48.

the board, start a wave down the trough. Describe the shape and behavior of the wave, and compare it with the wave set up by the finger.

d. Start a train of waves by means of the board. Compare with the train of waves set up by rapid tapping with the finger.

Reflection of Waves.—*e.* Start a straight wave with the board, as in *c*, and observe what happens when the wave reaches the farther end of the trough. Start a train of three or four waves, and observe whether they are all reflected. Can two sets of waves travel over the same surface in opposite directions and at the same time?

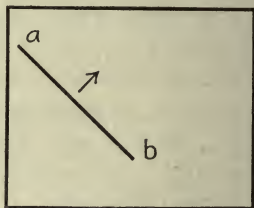


FIG. 49.

f. Start a train of waves with the board at an angle with the side of the trough, as in the position *ab* (Fig. 49). Draw a diagram showing the course of these waves before and after reflection. (Represent a train of waves by a number of parallel lines.) Describe the reflection of an oblique wave and its change of direction.

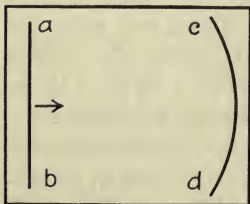


FIG. 50.

g. Start a circular wave at the center of the trough by a tap with the finger, and observe its reflection by the sides of the tank. Start a train of waves, and observe. Describe, with a diagram to illustrate.

h. Place the curved strip of tin as shown at *cd* (Fig. 50), and observe the reflection of a single straight wave and also a train of straight waves from its concave

side. Describe the shape and behavior of the reflected waves, and draw a diagram to illustrate.

Experiment 72. — *To study the reflection of sound from concave surfaces.*

Apparatus. — Two large concave reflectors; large funnel with rubber tube attached, for use as an ear trumpet; watch.

[This experiment can be performed only in a very quiet room. It should be set up in a room by itself, if possible.]

Experimental Work. — *a.* Stand one of the reflectors (*A*, Fig. 51) at one end of the table, and turn it so as to face toward the other reflector *B*, placed at a distance of 3 or 4 m. *B* is set

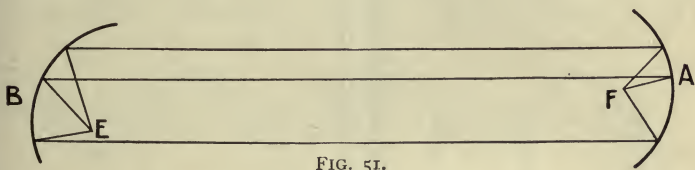


FIG. 51.

obliquely, as shown in the figure. Hang a watch in front of the center of reflector *A* at a distance from it equal to half the radius of its spherical surface. This point *F* is called the principal focus of the reflector.

Hold the ear at *E*, being careful to cover as little of the reflector with the head as possible, so as not to intercept the sound waves as they travel from *A* to *B*. Move the head slightly in different directions to find the position where the sound is loudest. When the ear is properly placed, the watch should be heard distinctly.

b. Instead of placing the ear at *E*, the reflector *B* may be turned so as to face squarely toward *A*, and the ear trumpet used to convey the sound to the ear. Place the funnel at the focus of *B*, and facing toward it, and the end of the tube in the ear. Try both ways.

c. With the ear at *E* or with the ear trumpet in position, observe the effect of turning *A* about a vertical axis toward one side, then toward the other.

EXERCISE 38. VIBRATION NUMBER OF A FORK

References. — Adams, 231-239 ; Coleman, 294-296 ; Car. & C., 204-205 ; Ches. G. & T., 185-186 ; Hoad. Br., 205-207 ; Hoad. El., 201, 222 ; Mumper, 172 ; Mil. & G., 456-457 ; Went. & H., 344.

Experiment 73. — *To find the number of vibrations per second of a tuning fork.*

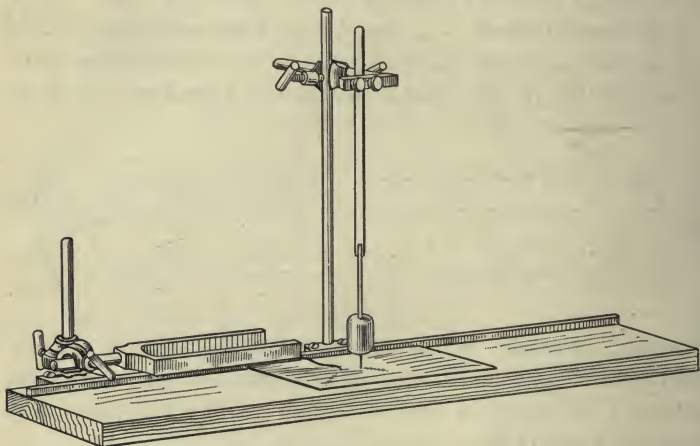


FIG. 52.

Apparatus. — Vibrograph with tuning fork, as shown in Figure 52 ; rubber mallet ; watch or small clock with second-hand ; fluid paste of whiting (or chalk dust) and alcohol ; small paint brush.

[The pendulum of the vibrograph should make not less than two double vibrations per second, and must have a heavy bob in order that the friction of the stylus may not affect its rate or stop it too quickly. The fork must be large and of low pitch, preferably not above 128, and capable of vibrating with a large amplitude for several seconds. Dealers supply forks especially designed for this purpose. The glass plate should be a foot or more in length, so as to accommodate at least two double vibrations of the pendu-

lum. The experiment is intolerably dirty in the hands of most pupils, if smoked glass is used. If smoked glass is preferred, it is recommended that the teacher smoke the plates and take the traces for the class.]

Method.—A stylus of fine wire or bristle is attached at the lower end of the pendulum, and another at the end of one of the prongs of the fork. These styluses lightly touch a plate of glass placed under them on the board. The glass is covered on its upper side with a thin coating of whiting and alcohol (or is smoked). With the fork and the pendulum vibrating, the glass is drawn quickly along the board to the right, and each stylus traces a wavy line on the glass, as shown in Figure 53, the line traced by the pendulum crossing and recrossing at regular intervals the one

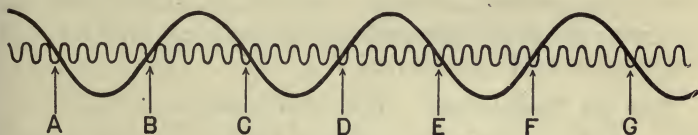


FIG. 53.

made by the fork. The time interval from *A* to *C* in the figure is the time of a double vibration of the pendulum, which is computed from the number of double vibrations which the pendulum makes in one minute. The number of vibrations made by the fork during one or more double vibrations of the pendulum is found from the trace on the glass. Having thus the number of vibrations of the fork in a known interval of time, the number of vibrations per second is easily computed.

Experimental Work.—Paint one side of the glass plate uniformly with the whiting and alcohol paste, and lay the plate aside to dry.

Count the number of vibrations that the pendulum makes in 60 sec., and compute the time of one double vibration.

After the glass is dried, place it in position with its right end under the styluses, being careful not to bend them. Adjust the

fork and the pendulum so that the styluses touch the glass lightly, within 2 or 3 mm. of each other at points which are in a line parallel to the sides of the base. Set the pendulum swinging through an arc of about 3 cm., strike the fork a vigorous blow to give it a large amplitude, and immediately draw the glass with a quick, steady motion to the right. Repeat, if necessary, till you have obtained a good trace of the fork covering not less than two double vibrations of the pendulum (from *A* to *E* in the figure), if this seems to be possible with the apparatus provided.

Count the double vibrations of the fork (estimating tenths) for the greatest number of *whole* double vibrations of the pendulum recorded on the glass (*A* to *C*, *A* to *E*, or *A* to *G* in the figure). Only whole double vibrations of the pendulum are considered, since, if the traces of the fork and the pendulum do not lie on exactly the same axis, adjacent spaces (as *BC* and *CD*) will not be exactly equal, one representing more and the other less than a single vibration of the pendulum.

Data and Computations. — Record as follows:—

No. of double vibrations of pendulum in 60 sec.	=
Time of one double vibration of pendulum	=
No. of vibrations of fork to — double vibrations of pendulum (counted)	=
No. of vibrations of fork to one double vibration of pendulum (computed)	=
No. of vibrations of fork per second	=

EXERCISE 39. INTERFERENCE AND BEATS

References. — Adams, 201, 220–223 ; Coleman, 298–299 ; Car. & C., 201–203 ; Ches. G. & T., 195, 200 ; Hoad. Br., 196–197, 204 ; Hoad. El., 212, 219 ; Mumper, 171, 177 ; Mil. & G., 468 ; Went. & H., 353–354.

Experiment 74. — *To study the interference of sound waves about a tuning fork.*

Apparatus (for Experiments 74 and 75).—Two tuning forks nominally of the same pitch, but giving from one to three beats per second; cylinder about 10 cm. in length and 2 cm. in diameter, consisting of an open roll of writing paper fastened with paste or a rubber band; rubber mallet; soft wax.

[To make the soft wax, melt together about nine parts, by weight, of beeswax and one part of Venice turpentine. Pour the melted wax into slender cylindrical paper molds. The paper may be removed as the wax is used.]

Experimental Work.—*a.* Hold a vibrating fork in a vertical position near the ear, and rotate it slowly. Have your companion tell you the position of the plane of the prongs (whether parallel with the side of the face, perpendicular to it, or at a greater or less angle) when the sound is loudest and when it is faintest to you. Describe the variations in the intensity of the sound, and the corresponding positions of the fork, during one rotation. Note whether there are positions in which the sound is inaudible.

b. With the vibrating fork held to the ear in the position in which the sound is faintest, have your companion cover one of the prongs with the paper cylinder, being careful not to touch the fork with it. Repeat till you are sure of the effect. State it.

Discussion.—State briefly the cause of the phenomena observed in these experiments. The full discussion may be left for the recitation.

Experiment 75.—*To study beats by means of two tuning forks of very nearly the same pitch.*

Experimental Work.—*a.* Sound both forks and hold them facing each other, about 2 cm. apart and close to the ear, with the planes of the prongs perpendicular to the side of the face. Note the frequency of the beats. Sound the forks and touch their stems to the table. Are beats produced?

b. Stick a piece of soft wax about the size of a pea to a prong of one of the forks, near the end, and note the effect on the fre-

quency of the beats. If the effect is too small to be noticed, use more wax. It is better to stick some wax on both prongs than a large quantity on one. The effect of the wax on the frequency of the beats will depend upon whether it has been put on the fork of the lower or the higher pitch. Prove this by removing the wax and putting it on the other fork. Does loading a fork raise or lower its pitch? Why?

- c. Tune the forks accurately to the same pitch by loading the right one till the beats cease. Do the beats become more or less frequent as the forks approach unison?

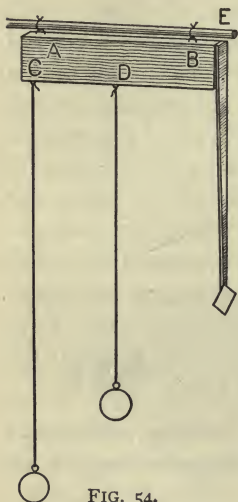


FIG. 54.

Experiment 76. — *To study a mechanical illustration of beats.*

Apparatus. — As shown in Figure 54.

[BC is a light, thin board about 20 cm. long, having a light pointer about 50 cm. long fastened to one end. The lower end of the pointer carries a small white card. The board is free to swing from a fixed support E, and carries two pendulums, one 80 to 100 cm. in length, the other about $\frac{3}{4}$ as long. The bobs of the pendulums are of equal mass, between 50 and 200 g. This experiment is due to Pro-

fessor Will C. Baker, of Queen's University, Kingston, Ont.]

Experimental Work. — Start the pendulums together, giving the longer one an amplitude of about 15° and the shorter an amplitude a few degrees greater. Carefully observe: (1) the gradual and regular alternation of the pendulums between vibration together (in the same phase) and in opposition (in opposite phase); (2) the behavior of the pointer; (3) the correspondence between the behavior of the pendulums and the behavior of the pointer.

Describe the observed phenomena, and show how the behavior of the pointer results from the behavior of the pendulums.

Class Discussion. — This experiment affords visible illustration of the mechanical relations involved in the production of beats in sound. Study the experiment from this point of view, and discuss it in the recitation.

EXERCISE 40. THE LAW OF LENGTHS¹

References. — Adams, 245 ; Coleman, 305-307 ; Car. & C., 210-211 ; Ches. G. & T., 199 ; Hoad. Br., 220-222 ; Hoad. El., 233-234 ; Mumper, 181 ; Mil. & G., 475 ; Went. & H., 347.

Experiment 77. *To find the relation between the length of a vibrating string and its pitch, the tension remaining constant.*

Apparatus. — Sonometer (Fig. 55) ; rubber mallet ; three or more forks, including c' (256 vibrations) and c'' (512) ; meter rod.

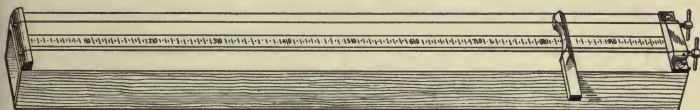


FIG. 55.

Experimental Work. — Adjust the bridge of the sonometer so that the vibrating segment of the wire is between 60 and 70 cm. long. Vary the tension till the wire is brought nearly into unison with the c' fork, then complete the adjustment to unison by varying the position of the bridge. In doing this, the vibrating fork may be held close to the ear (if the pupil is working alone) or touched to the sonometer or to the top of the table. The wire gives a better sound and one easier to compare with the fork if it

¹ The only law of vibrating strings requiring quantitative treatment in elementary physics is the law of lengths. This law underlies the discussion of the fundamental tone, overtones, and quality, both of strings and vibrating air columns, and may therefore be conceded a place in the laboratory course, although the other laws receive only qualitative illustration in the classroom.

is plucked near the middle with the end of the finger (not the nail). When the wire and the fork are nearly in unison, note the beats and tune till they disappear. Measure the length of the vibrating segment of the wire when unison is exact. *The tension must now remain unchanged throughout the exercise.* Displace the bridge and make a second trial. Make further trials if the disagreement exceeds 3 mm.

Repeat the above work with each of the forks provided, tuning only by varying the length of the wire.

Data and Computations. — Tabulate measurements and computations as indicated below. By length ratio for any tone is meant the ratio of the length of the wire for that tone to the length of the wire for c' . Compute the length ratio in each case, carrying to three decimal places. Find the true values of the length ratios from the law of lengths and the known vibration ratios of the forks used. For example, if the fork is g' , the vibration ratio is $\frac{3}{2}$, and, by the law of lengths, the length ratio is the reciprocal of this, or $\frac{2}{3}$.

TONE	LENGTH OF WIRE		MEAN LENGTH	LENGTH RATIO		ERROR	PERCENTAGE OF ERROR
	1st Trial	2d Trial		By Exp.	True		
c'	— cm.	— cm.	— cm.	—	—	—	—
e'	— cm.	— cm.	— cm.	—	.800	—	—
g'	— cm.	— cm.	— cm.	—	.667	—	—
etc.	— cm.	— cm.	— cm.	—	—	—	—

EXERCISE 41. SYMPATHETIC AND FORCED VIBRATIONS

References. — Adams, 214-215 ; Coleman, 310-315 ; Car. & C., 189-193 ; Ches. G. & T., 194-196 ; Hoad. Br., 198, 202-203, 205 ; Hoad. El., 213-215, 217-218 ; Mumper, 168-169 ; Mil. & G., 456, 463, 467 ; Went. & H., 351-352.

Experiment 78.—*To study the sympathetic vibration of tuning forks and resonators.*

Apparatus.—Two tuning forks of exactly the same pitch (shown by the absence of beats when sounded together); rubber mallet; soft wax; set of three or four tin tubes, or short pieces of large glass tubing, of different length and diameter.

[Forks giving a few beats per second can be permanently tuned to unison by filing a little off the inside of the prongs at the base of the higher fork or the free ends of the lower one. It will be more interesting if the tubes are of such sizes as to sound a major chord. A set of four tin tubes having lengths of 10, 8, 6.7, and 5 in., and diameters in proportion to the lengths, will do this.]

Experimental Work.—*a.* Place the stem of a sounding fork against the teeth. What evidence do you find that the stem vibrates as well as the prongs? Is the vibration of the stem longitudinal or transverse?

b. With one fork sounding and the other silent, place the ends of their stems together; and after they have been in contact one or two seconds, hold the fork that was silent close to the ear. It will be found to be vibrating audibly. How was its vibration produced?

c. Sound one of the forks and hold it and the other fork close together, facing each other, but not touching. After one or two seconds, hold the fork that was silent close to the ear. It should be sounding; if it is not, repeat. Explain.

d. Stick a bit of wax about twice the size of a pea near the end of a prong of one of the forks. This will slightly change the rate of vibration of the fork (see Experiment 75). Now repeat the experiments of paragraphs *b* and *c*, sounding either of the forks, and observe whether the silent fork is made to vibrate. State and account for the result.

e. Blow across the ends of the tubes in succession. Note that

each tube gives forth a sound of definite pitch. Hold the tubes close to the ears, using both ears at once, and note the faint sounds, like the roar of a sea shell, coming from them. Note whether the loudness of the sounds coming from the tubes is affected by scraping the foot on the floor while the tubes are at the ears. Note the pitch of these sounds. Is it the same in each case as that produced by blowing across the end of the tube?

The continuous sounds from the tubes are due to the various noises in the room. Consult texts for the explanation.

Experiment 79. — *To study the sympathetic and forced vibration of a sonometer wire.*

Apparatus. — Sonometer (Fig. 55) with two wires of the same size, and without a bridge.

Experimental Work. — *a.* Tighten one of the sonometer wires till it sounds a note of medium pitch, and tune the other wire to perfect unison with it. When the wires are nearly in unison, listen for a periodic pulsation of the sound (beats) when both wires are plucked. Tune till the beats cease. Now sound one of the wires, and the other will immediately begin to vibrate visibly. Stop the first wire, and the sound will be continued with considerable intensity by the other. Is this a case of sympathetic or forced vibration? How is it produced?

b. With the wires of the sonometer so nearly in unison that they give less than one beat per second when sounded together, sound only one of them and observe the behavior of the other. It should vibrate visibly for brief intervals, which alternate with intervals of rest. Observe that, as the difference in pitch is increased, these alternations of rest and vibration become more rapid, and the maximum amplitude of vibration becomes less, until presently the silent wire ceases to respond at all to the vibrations of the other. Account for this behavior of the wire.

EXERCISE 42. WAVE LENGTH BY RESONANCE

References.—Adams, 216–219; Coleman, 313; Car. & C., 193; Ches. G. & T., 194–197; Hoad. Br., 198–201; Hoad. El., 216; Mil. & G., 463–466; Went. & H., 349.

Experiment 80.—*To find, by means of a resonance tube, the length of the sound waves set up by a tuning fork of known vibration rate; and to compute the velocity of sound in air from these quantities.*

Apparatus.—Some form of resonance tube having an adjustable length (Figs. 56, 57, and 58); tuning fork; rubber mallet; rubber band; meter rod; access to a thermometer.

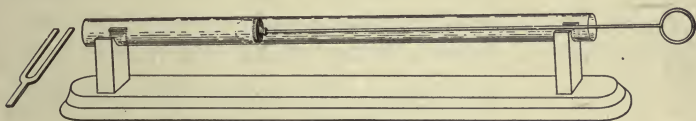


FIG. 56.

[For second resonance, the tube must be at least 105 cm. long with a c' fork (256), 85 cm. long with an e' fork, 75 cm. long with a g' fork, and 55 cm. long with a c'' fork (512).]

Formula.—As explained in the text-books, the length of an air column giving maximum resonance, in a tube closed at one end, is $\frac{1}{4}$ of the wave length of the sound for first resonance, and $\frac{3}{4}$ of the wave length for second resonance. The vibrating air column, however, extends beyond the open end of the tube a distance approximately equal to .3 of the inside diameter of the tube. Let L denote the wave length, l_1 the length of the tube for first resonance, and l_2 for second resonance, and d its inside diameter; then the algebraic statement of these relations is $l_1 + .3 d = \frac{1}{4} L$, and $l_2 + .3 d = \frac{3}{4} L$; from which

$$L = 4(l_1 + .3 d), \text{ for first resonance,}$$

$$L = 2(l_2 - l_1), \text{ for second resonance.}$$

It should be noted that the formula for second resonance does

not involve the "correction for the diameter," the increase of length for second resonance being exactly half a wave length.

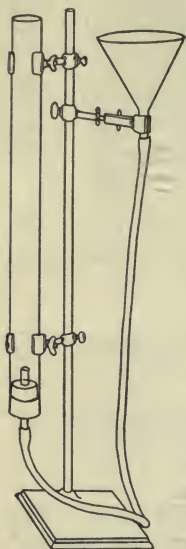


FIG. 57.

Method.—The vibrating fork is held within 1 or 2 cm. of the end of the tube, with the plane of the prongs either parallel or perpendicular to the axis of the tube. There will be almost no response from the tube unless the length of the air column is nearly that necessary for maximum resonance, the length of the column being determined by the position of the piston (which is of water with the apparatus shown in Figures 57 and 58). As the piston nears the correct position, the sound rapidly becomes louder. When this position is approximately located, the piston should be moved quickly but steadily (not with sudden jerks) back and forth past it several times, through a gradually diminishing distance, the experimenter being guided by the regular swelling and dying away of the sound. Meanwhile the rubber band, which is used to mark

the correct position, is gradually shifted into place. The adjustment is difficult and requires care.

In using the apparatus shown in Figure 57, water is poured in till it stands within 25 or 30 cm. of the top of the tube when the funnel is about half full. The height of the water in the tube is adjusted by raising and lowering the funnel, which is unclamped and held in the hand. With the apparatus shown in Figure 58, the length of the air column is adjusted by raising and lowering the tube in the jar of water.

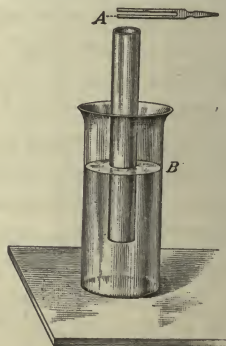


FIG. 58.

Experimental Work. — Two pupils will work together, one managing the fork and the other the piston. The vibrating fork must not be permitted to touch the tube, as the tube may be broken. Find the length of the tube for first resonance. Make a second trial, after moving the rubber band and piston out of position. If the two results do not differ by more than 3 mm., take their average as the value of l_1 . If the difference is more than this, repeat.

Find the length of the tube for second resonance, making two or more trials as before, and call their average l_2 . (If the apparatus of Figure 57 is used, it may be necessary to pour out part of the water. With the apparatus of Figure 58, the tube is too short for second resonance; in which case determine the length for first resonance with a fork of different pitch.)

Measure the inside diameter of the tube d ; record the vibration number of the fork n , and the temperature of the laboratory t .

Data and Computations. — Record as follows: —

Length of tube for first resonance	=	cm.
Ditto, second trial	=	cm.
Ditto, average value, l_1	=	cm.
Length of tube for second resonance	=	cm.
Ditto, second trial	=	cm.
Ditto, average value, l_2	=	cm.
Diameter of the tube (inside) d	=	cm.
Vibration number of the fork n	=	
Temperature of the room t	=	° C.
Length of wave $L = 4(l_1 + .3 d)$	=	cm.
Length of wave $L = 2(l_2 - l_1)$	=	cm.

Discussion. — 1. From the known vibration number of the fork and the value of L given by the experiment, compute the velocity of sound in air at the temperature of the room.

2. Compute the true value of the velocity at the temperature of the room, by adding to the velocity at 0° (332 m. per second) .6 m. for each degree above 0°.

3. Compute the percentage of error of your result.

IX. LIGHT

EXERCISE 43. SHADOWS; PIN-HOLE IMAGES; LAW OF INTENSITY

References. — Adams, 258-262, 304 ; Coleman, 332, 334, 337-338 ; Car. & C., 231-236 ; Ches. G. & T., 274-278, 280-281 ; Hoad. Br., 443-445, 447-448 ; Hoad. El., 489-491, 493 ; Mumper, 190, 192, 194 ; Mil. & G., 500-502 ; Went. & H., 362-364, 366.

Apparatus. — A flat gas jet, or lamp with flat wick ; meter rod attached to a board (Fig. 59), or rod alone ; three screens, referred to in the directions as *A*, *B*, and *C*, — *A* is 5 cm. square and

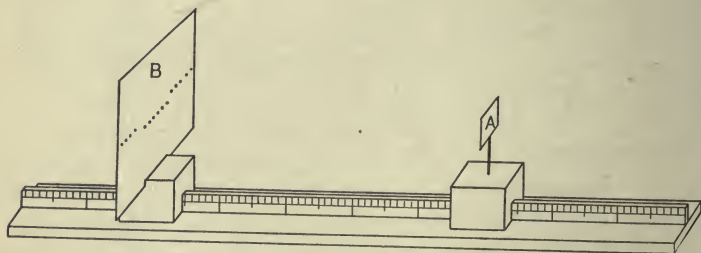


FIG. 59.

mounted on a wire (Fig. 59), *B* and *C* are about 18 or 20 cm. square, *B* having a broken horizontal row of small holes (Fig. 59), and *C* a small hole in the center ; short metric rule.

A gas burner on a low support should be provided for this and other exercises in light. The low form of Bunsen burner can be adapted to the purpose ; but a tip mounted on a block, such as is used for the screens and lenses, is preferable. It will be most con-

venient to have the screens, lenses, spherical mirrors, photometer, gas jet, and candles for the experiments in light mounted at the center of blocks of uniform size, in which a groove is cut so that they fit loosely on a meter rod, placed on edge. The rod thus serves as a guide to keep the parts of the apparatus in alignment, and the distances between them will be the distances between the corresponding ends (right or left) of the blocks upon which they are mounted. A board 100 cm. long and 8 or 10 cm. wide, with the meter rod fastened to it, makes a better support for the apparatus (Fig. 59).

Experiment 81. — *To study the formation of shadows.*

Experimental Work. — *a.* The room must be darkened for this exercise. Place the gas jet at an end of the meter rod, and place the screens *A* and *B* on the rod about 30 cm. and 80 cm. respectively from the same end, so that the shadow of the smaller screen falls on the larger. Turn the flame flatwise (parallel) to the screens, and adjust its height so that the darker part of the shadow (the umbra) covers all of the lower holes on *B*, but none of the higher holes on either side ; some, if not all, of the latter will then lie in the lighter part of the shadow (the penumbra), which borders the umbra. Now look toward the flame through each of the holes in succession, and observe what portion of the flame, if any, is visible from these different positions. State the connection between what you observe through each hole and the character of the shadow at that place. Draw a diagram of a horizontal section of the flame, screens, and parts of the shadow illustrating your explanation.

b. Turn the flame edgewise (perpendicular) to the screens, and note the change in the appearance of the shadow on *B*. Account for this change, and draw a section diagram to illustrate.

c. Remove *A*, and in its place hold a lead pencil vertically. Observe the shadow of the pencil on *B*, with the flame turned edgewise, then flatwise. With the flame flatwise, observe the varying width of the umbra and penumbra as the screen is moved up

to the pencil. Describe the observed changes in the appearance of the shadow, and draw diagrams to illustrate. (Remember that what we commonly call a shadow is only a cross section of it. A shadow is really the *space* from which the light is wholly or partly excluded by an opaque body.)

Experiment 82. — *To study the formation of images by small openings.*

Experimental Work. — *a.* Place the gas jet, turned flatwise, a short distance from the screen *C* (the one with the single hole at its center), and place the screen *B* close behind *C*. The light from the jet that passes through the hole in *C* forms an image of the jet on *B*. Move *B* toward and from *C*, and observe the effect on the size and brightness of the image. Account for the inversion of the image and its change of size when *B* is moved, referring to a diagram of a vertical section of the apparatus, the flame, and the image.

Account for the change in brightness when *B* is moved away from *C*.

b. Replace *C* with a sheet of paper in which you have made a small hole with the point of your pencil. Hold the paper so that the light through this hole will form an image on *B*, and note the effect of gradually enlarging the hole till it is 2 cm. or more in diameter. Describe and explain the changes in the image as the hole is made larger.

Experiment 83. — *To find how the intensity of light is affected by distance.*

Experimental Work. — *a.* Since this experiment deals with numerical relations, measurements must be made accurately. Place the screen *B* so that it (not its support) is exactly 60 cm. from the center of the gas jet, and place the small screen *A* exactly midway between them (*i.e.* 30 cm. from the center of the flame). Turn the flame down so as to get as nearly as possible a point source of light without losing the outline of the shadow of *A* on *B*. Meas-

ure the dimensions of A and the dimensions of its shadow on B . How do the dimensions of A and of its shadow on B compare? How do their areas compare? If A were removed, the light which now illuminates it would fall upon B and would cover the area now occupied by the shadow. How would the intensity of illumination on B then compare with the present illumination on A ? Why? Does the relative brightness of A and of the illuminated part of B seem to be in agreement with this conclusion? Both screens are partly illuminated by light from other sources than the gas jet. (How do you know?) Does this other light make the illumination of the screens more or less nearly equal than would be the case if the gas jet were the only source?

b. Repeat the experiment with A 30 cm. and B 90 cm. from the flame. Answer all the questions, changing them, where necessary, to agree with the present distances.

State the general relation between intensity of illumination and distance from the source.

EXERCISE 44. PHOTOMETRY

References. — Adams, 261–264; Coleman, 338–340; Car. & C., 235–238; Ches. G. & T., 281–282; Hoad. Br., 447–449; Hoad. El., 494–496; Mumper, 192–193; Mil. & G., 502–505; Went. & H., 366–367.

Apparatus. — A Rumford's or Bunsen's photometer (Figs. 60 and 61); 1 large candle and 5 small ones; 3 blocks for supporting candles; flat gas jet or lamp; meter rod.

[A Rumford's photometer, consisting of a screen of white cardboard and a rod, each supported vertically, is the most satisfactory form of photometer for elementary laboratory work, as it is least affected by the diffused light in an imperfectly darkened room or a room in which more than one piece of apparatus is in use. The box form of the Bunsen photometer is effective, but bulky and rather troublesome to manipulate. The author is of the opinion that laboratory work in photometry is hardly worth the

trouble. If a laboratory is not already equipped with satisfactory apparatus or a separate dark room for this work, he would recommend that such work be omitted, and that the principles of photometry be illustrated in the classroom only.]

Method.—We can make no reliable estimate of the relative brightness of unequally illuminated surfaces, but are able to judge with considerable accuracy whether two adjacent surfaces, seen at the same time, are equally illuminated; hence, with all forms of photometers, the distances of the lights compared are adjusted so as to give equal illumination.

Rumford's Photometer.—Figure 60 shows the adjustment of this apparatus in comparing the illuminating powers of a candle



FIG. 60.

and a gas jet. The rod casts two shadows on the screen, one being due to the exclusion of the candle light, the other to the exclusion of the gas light. Each source of light illuminates the shadow due to the other; hence, when their relative distances from the screen are such that the shadows are equally dark (*i.e.* equally illuminated), we know that the lights give equal intensity of illumination at these distances; and, knowing the law, we can compute their relative illuminating powers from these measured distances. Conversely, if we know the relative illuminating powers of the two lights, the experiment demonstrates the law. (This is the problem of Experiment 84.) The room must be quite dark, or other sources of light will make the shadows too faint for comparison.

Bunsen's Photometer.—The box form of this photometer is shown in Figure 61. The box serves the purpose of shutting out diffused light from other sources. The essential part of the photometer is a vertical screen of white paper, having a translucent spot made by applying a drop of hot paraffine. If the two sides of the paper are unequally illuminated, the spot will appear darker than the rest of the paper when viewed from the more strongly illuminated side, and lighter when viewed from the less strongly illuminated side. The spot appears darker in the first case because it reflects less light to the eye than the rest of the paper does ; in

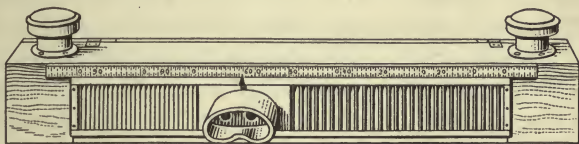


FIG. 61.

the second case it appears bright on account of the light it transmits from the other side. When both sides are equally illuminated, the spot nearly disappears and looks exactly alike on both sides. The adjustment of the photometer consists in moving the screen from side to side along the line between the two lights that are being compared, until the position is found where the spot has the same appearance from both sides. We know then that the two lights give equal illumination at their respective distances. The adjustment of the screen is much more accurately made with the aid of two small mirrors, so placed that the two sides of the spot can be seen in them at the same time.

Experiment 84.—*To find the relation between the illuminating powers of two lights and the distances at which they give equal illumination.*

Experimental Work.—Mount a small candle at the center of one block and four small candles in a line on another. With the Rumford photometer, place the single candle at a distance of

about 40 cm. from the screen, and the four candles at such a distance that the two shadows are equally dark. The rod that casts the shadow should be within a few centimeters of the screen, and the lights so placed that the shadows are separated only by a narrow line. The line of four candles should be parallel to the screen. In making the adjustment, move one of the lights toward the screen till one of the shadows is lighter than the other, then move it away till the same shadow is darker than the other. Repeat several times, gradually diminishing the distance covered in the to-and-fro motion, and finally estimate the correct position as closely as possible. With the Bunsen photometer, place the lights at the ends of the meter rod, and move the screen to one side till that side of the spot is darker than the other, then back again till the other side is darker; and repeat through a gradually diminishing distance till you have found the position where the two sides of the spot look just alike.

Care must be taken to see that the five candles are burning as nearly equally as possible; for the light from any one of them may vary, if left to itself, 50 % or more in the course of a few minutes, and the experiment is based upon the assumption that the four candles give four times as much light as the single candle. Use scissors to trim the wicks before adjusting the distances, if the candles are burning unequally.

When the adjustment for equal illumination has been made, measure the distances of the lights from the screen. Make and record two or three trials, leaving the position of one of the lights unchanged with the Rumford photometer, and the position of both lights unchanged with the Bunsen.

Data and Computations. — Let P_1 denote the illuminating power of the single candle and D_1 its average distance from the screen; P_2 the illuminating power of the group of four candles and D_2 its average distance. It is assumed that $P_2 = 4 P_1$. This assumption may, however, be in error by as much as 10 or 15 %, even with careful attention to the candles. Record as follows: —

Distance of single candle	=	cm.
Ditto, second trial	=	cm.
Ditto, average, D_1	=	cm.
Distance of group of four candles	=	cm.
Ditto, second trial	=	cm.
Ditto, average, D_2	=	cm.
Ratio of illuminating powers of the lights $P_1 \div P_2$	=	.25
Ratio of distances of the lights $D_1 \div D_2$	=	
Ratio of the squares of the distances $D_1^2 \div D_2^2$	=	
Percentage of difference between $P_1 \div P_2$ and $D_1 \div D_2$	=	%
Percentage of difference between $P_1 \div P_2$ and $D_1^2 \div D_2^2$	=	%

Is the difference between either of these pairs of ratios within a reasonable limit of experimental error (say 15 %)? If so, what is the answer suggested to the question stated as the object of the experiment?

Experiment 85.— *To measure the candle power of a small candle and a gas jet or a lamp.*

Experimental Work.— *a.* Use the photometer to find the ratio of the illuminating power of a small candle to the large one, *i.e.* taking the large candle as the standard, find the candle power of the small candle.

b. Find the candle power of the gas jet or the lamp (whichever is provided), when turned to a moderate height, by comparing it with the large candle. Have the flame turned flatwise toward the screen.

EXERCISE 45. PLANE MIRRORS

References.— Adams, 265–266, 304–307; Coleman, 342–348; Car. & C., 239–245; Ches. G. & T., 283–290; Hoad. Br., 450–455; Hoad. El., 497–503; Mumper, 195–197; Mil. & G., 506–508, 528–530; Went. & H., 369–371.

Apparatus.— A small, rectangular plane mirror, with support (if mounted with a free space of about 5 mm. under it, as shown

in Figure 62, it will serve for both experiments following); metric rule; protractor; pins.

[In using common mirrors for the study of images, an error is involved, due to two refractions of the light at the front surface.

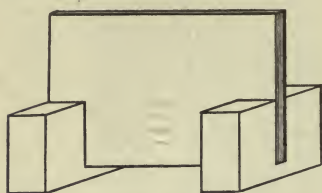


FIG. 62.

These refractions diminish the distance of the image by about two thirds the thickness of the mirror. Hence thin mirrors are to be preferred. The error is reduced one half, if, in locating the image by the method of Experiment 87, the pin that is made to coincide with

the image is viewed through an unsilvered portion of the glass. The error will be entirely avoided if the front surface of a piece of plate or window glass is used as the reflecting surface. The image thus obtained will be quite distinct if the glass is backed with black paper or cloth. Since both surfaces reflect, two images will be seen. The rear image will disappear and the other will be more distinct if the back of the glass is painted black.]

Experiment 86.—*To find the position of a point image in a plane mirror by sight lines; and to find the relation between the position of the point and its image, and the relation between the angles of incidence and reflection.*

Method.—A sheet of paper is laid on the table, and the mirror placed on it in a vertical position marked by the line AB (Fig. 63). A pin is stuck in a vertical position at O in front of the mirror, and the point where it pierces the paper is taken as the object whose image in the mirror is to be located. If this image has a fixed position behind the mirror, all lines drawn on the paper in front of the mirror and extending in the direction of the image will intersect

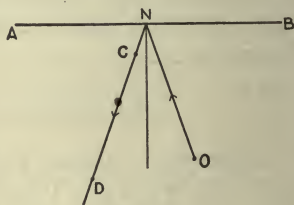


FIG. 63.

at the position of the image when produced; and this position will be determined by the intersection of any two such lines. Lines thus drawn are called *sight lines*, *i.e.* lines along which the observer sights toward the image. A sight line is determined by means of two pins, placed vertically several centimeters apart (as at *C* and *D* in the figure) and exactly in line with the image of *O*, the pin at *C* being placed first, at any point near the mirror and on either side of *O*. A line is then carefully drawn with a rule and a *sharp* pencil through the points *C* and *D*, and produced after the mirror is removed.

Experimental Work. — Draw a line *AB* about 10 cm. long on a large sheet of paper, leaving a space of not less than 8 cm. on each side of it. Stand the mirror so that the plane of its reflecting surface passes exactly through this line. In doing this, look vertically down along the reflecting surface. (The reflecting surface of a common mirror is, of course, the rear surface. If unsilvered glass is used, either with or without the back painted black, its front surface is the reflecting surface. If the back surface is not painted or ground, it, too, will cause an image, slightly farther back than the first; but this image is to be disregarded.) Stick a pin vertically 3 or 4 cm. in front of the mirror, and mark the point where it pierces the paper *O*. This point is the object whose image is to be located.

Draw four sight lines directed accurately toward the image, and determined in the manner described above, two of them lying on each side of *O*. In sighting, place the eyes on a level with the paper, close one of them, and have the pins parallel. The sight lines should all make wide angles with each other; since, if any two are nearly parallel, a slight error in the direction of either will make a relatively large error in their point of intersection. If necessary in order to get wide angles, the mirror may be shifted parallel to itself along the line *AB*.

Remove the mirror and produce the sight lines on the other side of *AB*. If the image has the same position when viewed

from different directions, the sight lines, if accurately determined, will all intersect at the same point. Repeat the experiment if the points of intersection do not coincide within 2 mm. With careful work they should coincide within 1 mm.

Mark the point of intersection of the sight lines I . Draw the line OI . Measure with the protractor, and record in the figure, one of the angles formed by AB and OI . What should this angle be? Measure the segments of OI formed by its intersection with AB , and record in the figure. How should these segments compare?

It is evident that, when you were looking along any one of the sight lines, the light by which you saw the image came to the eye along that line, having been reflected by the mirror at the point where the sight line meets AB . Mark this point N . Draw the line ON , representing the incident ray; and draw the perpendicular to AB at N (using the protractor). Measure with the protractor, and record in the figure the angles of incidence and reflection. Repeat this construction and measurement for one other sight line. How nearly do the constructed angles of incidence and reflection agree with the law? With careful work the error will be less than 1° .

The sheet on which this work is done may be pasted in your record book, or an accurate copy of the figure made by placing the sheet on the one to which the figure is to be transferred, and pricking two pin points through to mark the position of each line.

Experiment 87.—*To find the position of a point image in a plane mirror by direct observation.*

Preliminary Study (to precede the laboratory hour).—Hold a pencil at arm's length, pointing upward, in one hand, and a second pencil at about two thirds that distance, pointing downward, in the other hand. Bring the points of the pencils into line with one eye, the other eye being closed. The points will seem to touch, although they are really 15 cm. or more apart. Without

moving either pencil, look at them with the other eye, closing the first, and note the change in the apparent positions of the pencils. Repeat, closing first one eye, then the other, with the pencils in line with each eye in turn, until you are familiar with the effects, and have discovered the reason for the apparent shifting of the pencils when you change the eye with which you look. Now look with both eyes, first at the nearer pencil, then at the farther one, and note that when you are looking at either pencil, the other appears double; note also that while looking with both eyes, there is no misjudgment of distances. Look again with each eye in turn, as you gradually move either pencil toward the other; and note that the apparent shifting of the pencils from side to side becomes less, and ceases only when the points are actually in contact.

Familiarity with these phenomena of vision will be of great assistance in the following experiment, and in several later ones as well, where the work has to do with the actual position of images. The apparent displacement of an object, due to a change in the position from which it is viewed, is called *parallax*.

Experimental Work.—Draw a line AB across the middle of a large sheet of paper, and stand the mirror with its reflecting surface vertically over it. Stick a pin in a vertical position at a distance of several centimeters in front of the mirror. With the eyes just above the level of the table, look under the mirror at a second pin, held vertically in the fingers behind the mirror; and place this pin where it appears to coincide with the image of the pin in front. In doing this, look with both eyes, and move the head into various positions. When the pin is correctly placed, it will accurately fit the image from all points of view.

When the image is correctly located, draw a line connecting it with the object. Measure and record the segments into which this line is divided by AB , and the angle between the lines. If time remains, see if you can get more accurate results by further trials, placing the object in a different position each time.

EXERCISE 46. MULTIPLE IMAGES

(INVENTIVE)

References. — Adams, 308–309; Coleman, 349; Car. & C., 246–247; Hoad. Br., 456–458; Hoad. El., 504–506; Mil. & G., 532; Went. & H., 373.

Experiment 88. — *To study the formation of images by multiple reflection from two plane mirrors.*

Apparatus. — Two plane mirrors, each with a support to hold it in a vertical position; rule; candle, mounted; some small object having right side distinguishable from left and front from back; etc.

Suggestions. — In performing this experiment it is necessary to bear in mind that the reflected light travels *from the direction of*

the image, just as if the image were the real source.

The principal points that come within the scope of the experiment are as follows: —

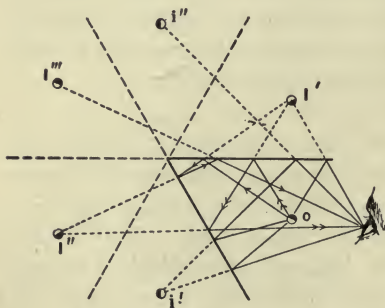


FIG. 64.

1. With the mirrors at a given angle, to note the number of images formed and their exact location with respect to the object, the mirrors, and the images of the mirrors.

2. To determine the number of reflections by which each image is formed, and the order in which these reflections occur (*i.e.* from which mirror first).

3. To account for the number and position of the images, from the known reflections of the light and the law of reflection.

4. To observe which of the images have their right and left sides reversed and which have not, and to determine why.

5. To determine the path of a ray of light from the object to the eye, in viewing any one of the images from a given position.

6. To construct diagrams illustrating the answers to these questions.

Make a study of these questions and of others that may occur to you, devising methods of procedure for yourself. The mirrors may be at any angle, an angle of 90° being the simplest case. The case of parallel mirrors should be included. The accompanying figures

will afford suggestions as to the character of the diagrams. If a kaleidoscope is provided, investigate its construction and action.

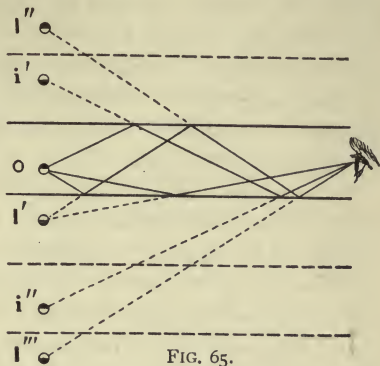


FIG. 65.

EXERCISE 47. THE CONCAVE MIRROR

References. — Adams 310-316 ; Coleman, 350-355 ; Car. & C., 249-255 ; Ches. G. & T., 295-298 ; 302-305 ; Hoad. Br., 460-466 ; Hoad. El., 507-512 ; Mumper, 198 ; Mil. and G., 538-545 ; Went. & H., 374-376, 379.

Experiment '89. — *To find the focal length and radius of curvature of a concave mirror, and to study the formation of real and virtual images by it.*

Apparatus. — Concave mirror ; meter rod ; mounted candle ; cardboard screen.

[A silvered mirror of glass having a diameter of 10 or 11 cm. is adapted to this experiment. These can be obtained in a wooden frame with a handle, and also in a light metal frame, which is preferable. It will be found convenient to have them mounted on blocks, uniformly with the screens, lenses, etc., as suggested under Exercise 43.]

Experimental Work. — *a.* Hold the mirror in the sunlight and facing exactly toward the sun, and focus the light on a piece of paper. In doing this, hold the paper a little to one side, so as not to cut off the light from the mirror; turn the mirror so that the reflected light falls upon the paper and move the paper toward or from the mirror into the position where the spot of light is the smallest. The spot is an image of the sun, and if the adjustment is right, it will be round.

b. Stand the mirror on the table near a window, and turn it facing toward some distant object, as a house or a tree, at least 200 ft. away. Stand the cardboard screen on the table in front of the mirror and a little to one side of the direct line between the mirror and the object (in order not to intercept the light), and adjust its distance from the mirror till the image of the distant object is sharply defined upon it. If the weather is not too cold, raise the window in making this adjustment, for the light is distorted by the wavy surfaces of common window glass, and this makes perfect focusing impossible. Measure the distance from the image to the mirror. This is the focal length f of the mirror (the rays from *any point* of the object being sensibly parallel).

c. Move the screen a little to one side, leaving it in the plane of the image and near it so as to mark its position. Place the head very nearly in line between the mirror and the object, at a distance of about a meter from the mirror, and look toward the mirror at the place *in the air* beside the screen, where the image is. If this is correctly done, the image will be very distinctly seen in its real position in front of the mirror. It is difficult for the beginner to avoid looking beyond the image into the mirror; in which case the image will appear to be in the mirror and will be blurred, — just as the finger appears blurred and double when you hold it before you and look at something beyond it. If you are unsuccessful after a brief trial, pass this for the present, and try again after finishing the exercise.

d. The remainder of the exercise requires a darkened room. Place the lighted candle at one end of the meter stick, and stand

the mirror at the other end. Place the eyes on a level with the candle, and look past it toward the mirror. A number of real and inverted images of the candle will be seen in line between it and the mirror. The one that is the largest, the farthest from the mirror, and the brightest is the one that is formed by a single reflection at the concave silvered surface, and is the one to be studied. The others are due to multiple reflections within the mirror. Turn or tip the mirror a little, if necessary, to bring the images into line with the candle, and be careful to find the principal one. Ignore the others. Move the candle along the meter rod till the tip of the flame coincides with the tip of the image, turning or tilting the mirror, if necessary. Object (the tip of the flame) and image are now at the center of curvature of the mirror. (Why?) Measure their distance from the mirror. This is the radius of curvature r . Compare $r/2$ with f , found in paragraph *b*.

e. Starting with the candle at the center of curvature, carry it slowly across the room as far as you can from the mirror, while your companion, standing near the mirror, observes the simultaneous change of size and position of the image. Measure the distance of the image from the mirror when the object is farthest away, focusing the image on the screen for the purpose, if found more convenient. Compare this distance with f . What would be the final position of the image if the object were carried farther away indefinitely?

f. Again starting with the candle near the center of curvature, move it slowly toward the principal focus, meanwhile keeping watch of the changing size and position of the image by focusing it on the screen. Continue till the image is focused upon a distant wall of the room, or as far away as it can be seen. With this adjustment, measure the distance of the candle from the mirror, and compare with the distance of the image when the candle was at its greatest distance. If the candle were moved up to the principal focus, where would the image be?

g. Move the candle from the principal focus toward the mirror, while observing the change in the size and position of the image,

which is now virtual, erect, and behind the mirror. (A faint virtual image of constant size will also be seen. This is due to partial reflection from the front surface of the mirror, which is plane.) Estimate the relative distances of image and object from the mirror.

Discussion. — From a study of the text you will learn how the facts observed in this exercise result from the law of reflection and the curvature of the reflecting surface. The text also discusses the construction of explanatory diagrams. From a study of the text and the results of the experiment, find the answers to the following questions : —

1. What happens, after reflection, to the diverging cone of light that falls upon the mirror from *any one point* of the object (*a*) when the distance of the object is greater than the focal length ; (*b*) less than the focal length ; (*c*) equal to the focal length ?

2. What behavior of the reflected light gives rise to (*a*) a real image ; (*b*) a virtual image ? (Remember that a focus is a point, and that images have size. Be definite in your answer.)

3. Under what conditions is (*a*) a real image formed ; (*b*) a virtual image ?

4. With rule and compass draw accurate figures showing the size and position of the image formed by a concave mirror —

When the object is large and at a relatively great distance (illustrating paragraph *b* of the experiment).

When the object is a point at the center of curvature (illustrating paragraph *d*).

When the object is beyond the center of curvature, but not at a great distance (illustrating paragraph *e*).

When the object is between the principal focus and the center of curvature (illustrating paragraph *f*).

When the object is only slightly nearer the mirror than the principal focus (illustrating paragraph *g*).

When the distance of the object from the mirror is about $\frac{1}{4}$ the focal length (illustrating paragraph *g*).

Use the same radius of curvature in all the above figures, and in all but the first two represent the object by an arrow of the same length. The object cannot be represented in the first diagram, being too far away and too large to be represented to scale.

EXPERIMENT 48. PHENOMENA DUE TO REFRACTION

References. — Adams, 267–268 ; Coleman, 358–359 ; Car. & C., 256–257 ; Ches. G. & T., 310–311 ; Hoad. Br., 467–470, 474 ; Hoad. El., 515–518, 522 ; Mumper, 200 ; Mil. & G., 510 ; Went. & H., 381–382.

Experiment 90. — *To study the refraction of light in passing from glass into air, and the apparent displacement of objects resulting from such refraction.*

Apparatus. — A rectangular piece of thick plate glass, ground and polished on two opposite ends ; glass prism with flat ends and wide faces ; rule ; pins.

Experimental Work. — *a.* Stand the prism on end on this page, and look at the printing through it. Note the apparent elevation of the part of the page seen through the prism. Estimate the ratio of the real length of the prism to its apparent length, as you look through it. Lay the piece of plate glass on the page, and observe whether there is a similar apparent elevation of the part seen through it. Stand the plate on one of its polished ends and look down through the width of the glass at the printing. Result?

b. Lay a sheet of paper on the table, and lay the glass plate on it near the farther end (Fig. 66), with its polished ends at front and rear. Stick pins vertically at *A*, *B*, and *C*, close to the glass — *A* at the middle of the farther end, *B* and *C* about 2 cm. apart

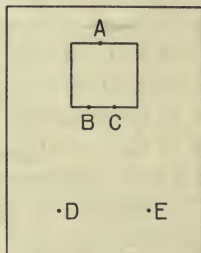


FIG. 66.

at the front end. Place the eyes just above the level of the table, close one of them, and move the other into line with B and the apparent position of A , seen through the glass. Place another pin exactly in this line, 5 or 6 cm. toward the eye from B ; and mark its position D . The line DB indicates the direction in which A is seen through the glass, when the eye is in its present position. Obviously, the light by which A is seen from this position emerges from the glass at B (since B appears to be in line with A), and traverses the path BD to the eye. Its path through the glass is along the straight line AB . Since A , B , and D are not in a straight line, it follows that the light undergoes a change of direction (refraction) at B . It is important to note that A is seen in the direction *from which the light is traveling as it enters the eye*, — a general truth that has become familiar in the study of images formed by reflection. In fact, what is seen through the glass is an image of A formed by refraction.

In the same way place a pin (at E in the figure) in line with C and the apparent position of A .

Draw the outline of the glass plate on the paper; remove the plate; draw the lines DB and EC , and produce them as dotted lines to their point of intersection; letter this point A' ; draw the lines AB and AC ; and place arrowheads on the parts of the broken lines ADB and ACE . These broken lines with the arrowheads represent actual paths of light from A through the glass and into the air; the dotted lines $A'B$ and $A'C$ indicate apparent paths of light from the image A' .

Is the refraction to the right or the left at B ? Does this cause A to appear to the right or the left of its true direction? Answer the same questions for the refraction at C .

c. Replace the glass plate in its former position, and find the apparent direction and position of A when viewed through the glass along the line perpendicular to the front surface. Is its apparent position the same as when viewed along the lines DB and EC ? (Answer from direct observation with one eye and also with both.) Does it appear to be to the right, to the left, or

in its real direction? What does this indicate concerning the refraction (bending) of the ray that is perpendicular to the surface of the glass?

d. Move the head to one side so as to view *A* more obliquely through the glass than *DB* or *EC*, and note the change in its apparent position, using both eyes for the observation and without placing pins. State the result.

Copy the figure accurately or paste the sheet in your record book.

Experiment 91. — *To study the apparent displacement of objects under water, due to refraction at the surface.*

Apparatus. — Glass jar, preferably rectangular; bit of tin or other small object that sinks in water; large jar of water; beaker; rule; mop cloth.

Experimental Work. — *a.* Pour water, a little at a time, into the smaller jar, while looking down at the bottom of the jar through the water; and observe the apparent elevation of the bottom above the level of the table top. How does the apparent elevation of the bottom change as the depth of the water increases? Estimate the ratio of the real depth of the water to its apparent depth as you look vertically down through it. Does this ratio appear to change or to remain constant as you increase the depth of the water? Figure 67 represents a pencil of light from a point of the bottom. Copy and complete the figure so as to explain the apparent elevation of the bottom. Represent the apparent path of light by a dotted line.

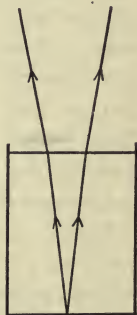


FIG. 67.

b. Fill the jar nearly full of water. With the rule held exactly vertical, gradually lower an end of it into the water, observing any change in the apparent length of the immersed portion, when viewed through the surface of the water. Repeat the observation,

raising and lowering the rule several times. Does the immersed portion appear to be in its real direction (vertical) or does it appear to be oblique? Does the appearance of the immersed portion indicate an apparent oblique or vertical displacement of any point from its real position? Copy and complete Figure 68 so as to explain the apparent displacement of the immersed end of the rule.

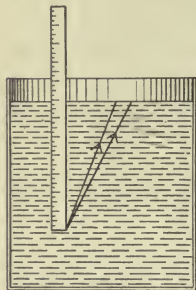


FIG. 68.

c. Observe any change in the appearance of the immersed portion of the rule, held in a fixed vertical position, as you view it more and more obliquely through the surface of the water, gradually lowering the head till the eyes are nearly on a level with the surface. Draw a figure represent-

ing and explaining the appearance, when the line of sight is very oblique.

d. Hold the rule or a pencil oblique and partly immersed in water, and note the apparent length and direction of the immersed portion as seen through the surface. Copy Figure 69 and complete it, showing the apparent position of the immersed part of the pencil.

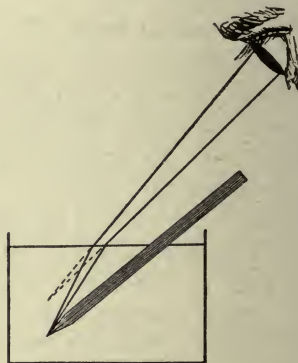


FIG. 69.

Pupils often confuse the actual direction of bending of the light with the apparent direction of bending of the object. Referring to your completed copy of Figure 69, show the relation between these directions.

e. Drop the piece of tin (or other small object) into the jar of water, and look down at it while disturbing the water with your finger. Describe and explain the effect of the motion of the surface.

EXERCISE 49. SNELL'S LAW OF REFRACTION; INDEX OF REFRACTION OF GLASS

References. — Adams, 268–270; Coleman, 360–362; Car. & C., 258–260; Ches. G. & T., 312; Hoad. Br., 468–471; Hoad. El., 515–519; Mumper, 202; Mil. & G., 523–525; Went. & H., 381.

Apparatus. — Rectangular piece of thick plate glass, ground and polished on two opposite ends, and having scratches perpendicularly across the polished ends at *A*, *B*, *C*, and *O* (Fig. 70); pencil compass; metric rule; pins.

Experiment 92. — *To study the relation between the directions of the incident and refracted rays for different angles of incidence; and to find the index of refraction of a piece of plate glass.*

CAUTION. — In this experiment the numerical values are obtained from a diagram, which must therefore be constructed as accurately as possible. Points are to be located by means of minute dots, lines drawn very thin with a rule and sharp pencil, perpendiculars accurately at 90° , and distances measured to tenths of a millimeter. A pupil who has had practice in mechanical drawing should be able to get results agreeing with the law within 1%; for others an accuracy of 2% is very good and an error of 3% satisfactory.

Experimental Work. — Have the pencil very sharp, and keep it so. Draw a thin straight line *MN* (Fig. 70) across the middle of a large sheet of paper, and lay the glass plate on it with one of the polished ends exactly at the line, as shown in the figure. The plate should have scratches perpendicularly across the polished ends at *A*, *B*, *C*, and *O*. Locate the exact position of these scratches on the paper by minute dots. If there are not scratches on the glass, stick pins

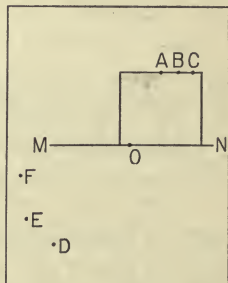


FIG. 70.

vertically at these points, close to the glass. The glass must be left exactly in this position until pins have been located at D , E , and F , as follows:—

Place the eyes on a level with the table, close one of them, and place a pin near the front edge of the paper exactly in line with the scratch (or pin) at O and the image of the scratch at A . Letter this point D . Similarly, locate a pin at E in line with O and the image of B , and another at F in line with O and the image of C .

Remove the plate and draw very accurately the broken lines DOA , EOB , and FOC , extending them in both directions to the edge of the paper. To distinguish the different incident and the corresponding refracted rays, place a single arrowhead on DO and on OA , two arrowheads on EO and on OB , and three on FO and on OC .

Fold a straight edge of a sheet of paper to form an accurate right angle, and use it to erect a perpendicular to MN at O .

(Do this with the greatest care.) Letter this perpendicular XY .

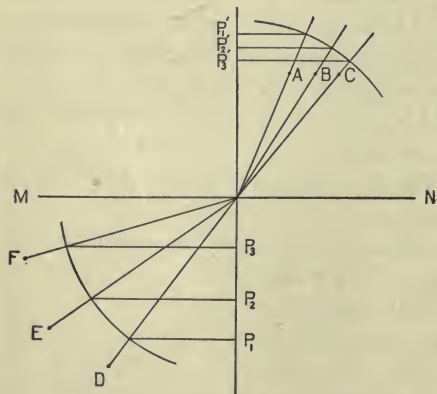


FIG. 71.

Let P_1 , P_2 , and P_3 denote the perpendiculars constructed for the three refracted rays, and P_1' , P_2' , and P_3' the perpendiculars for the corresponding incident rays. Measure these perpendiculars,

estimating carefully the tenths of a millimeter, and record their lengths beside them.

Paste or copy this figure in your record book.

Data and Computations.—Compute the ratios P_1/P_1' , P_2/P_2' , and P_3/P_3' to three decimal places, and find the percentage of difference between the greatest and the least of them. According to the law of refraction, they should be equal.

Any one of these ratios is an experimental value of the index of refraction of the glass plate, and their average is to be taken as the value of this quantity as given by your experiment. Compute it.

Discussion.—Snell's Law, as commonly stated, involves the use of the term "sine of an angle." In any right triangle the ratio of either leg to the hypotenuse is called the sine of the angle opposite to that leg. Thus in Figure 72 the sine of angle A is BC/AB or $B'C'/AB'$ or $B''C''/AB''$ (all of which ratios are equal, since the triangles are similar), and the sine of angle B is AC/AB . The usual form of writing this is $\sin A = BC/AB$, and $\sin B = AC/AB$. The sine of an angle increases as the angle increases from 0° to 90° , but *they do not increase proportionally*. In other words, while the greater of two acute angles always has the greater sine, the angles and the sines are not in proportion.

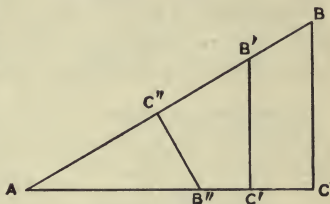


FIG. 72.

Let the radius of the circle in Figure 71 be denoted by R ; then the sine of the smallest angle of incidence is P_1'/R , and the sine of the corresponding angle of refraction is P_1/R . The ratio of the sine of the angle of incidence to the sine of the angle of refraction is therefore $P_1'/R : P_1/R$, or P_1'/P_1 . If we suppose the light to be traveling from air to glass (reversing the arrow-heads in your figure), the angles of incidence and refraction will

simply be interchanged. We shall then have as the ratio of the sine of the angle of incidence to the sine of the angle of refraction P_1/P_1' , P_2/P_2' , and P_3/P_3' for the three cases, respectively, and we have learned that these ratios should be equal. In the customary language, we have found that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is constant (within a certain limit of experimental error) for air and the glass plate, for the different angles of incidence.

It should be noted that the index of refraction of a substance is defined as the ratio of the sine of the angle of incidence to the sine of the angle of refraction for light traveling *from* a vacuum (or air) *into* the substance. This is why we have assumed the direction of the light in the above experiment to be reversed.

Experiment 93.—*To find whether the ratio of the real width of the piece of plate glass to its apparent width, viewed through it perpendicularly to a polished end, is equal to its index of refraction.*

Experimental Work.—Paste a strip of paper B (Fig. 73) on one side of the glass plate used in Experiment 92, so as to over-

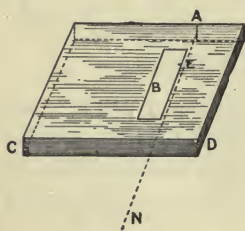


FIG. 73

lie the perpendicular from one of the scratches A . Hold the plate in one hand on a level with the eyes, and look with both eyes at the scratch through the polished end CD , along the line NA perpendicular to CD ; and at the same time look through the air at the sharp point of your pencil, as you place it in apparent coincidence with the scratch.

In doing this you will find it helpful to move the pencil forward until it is evidently a little nearer than the image of the scratch, then back till it is a little farther than the image, gradually diminishing the distance till the exact point is located. Shifting the head very slightly from side to side is sometimes helpful. It should be possible to locate the image of the scratch within .2 or .3 mm.

Make a dot on the paper marking the position of the image. Measure the distance from this dot to the surface CD . This is the apparent width of the glass. Measure its real width.

Computation and Conclusion.—Divide the real width by the apparent width; and compare the quotient with the index of refraction of the glass as found in Experiment 92.

It can be shown mathematically that the quotient of the real width of a transparent body by its apparent width, when viewed perpendicularly to the refracting surface, is the index of refraction of the substance.

EXERCISE 50. REFRACTION THROUGH A PLATE AND A PRISM; TOTAL REFLECTION

References.—Adams, 272-276, 278; Coleman, 365-369; Car. & C., 262-263, 266-268; Ches. G. & T., 315-318; Hoad. Br., 472-473, 475-476; Hoad. El., 520-524; Mumper, 200-201, 203; Mil. & G., 511-515; Went. & H., 383-385.

Experiment 94.—*To find the path of a ray of light through a glass plate and through a glass prism; and to observe the apparent displacement of objects seen through each.*

Apparatus.—A rectangular piece of thick plate glass; a triangular prism with flat ends and wide faces; rule.

Experimental Work.—*a.* Draw a straight line AB (Fig. 74) a few centimeters long on a page of your note book; stand the glass plate on end obliquely to the line, and mark its outline CD on the paper. Lay the rule on the paper in front of the glass; and, sighting along its edge with one eye, place the edge in line with AB as seen through the glass. Draw a line on the paper in this position, and letter it EF . Raise the plate so as to view AB under it, and note the actual

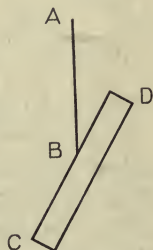


FIG. 74.

position of AB relative to EF . Note the apparent shifting of AB parallel to itself as the plate is again lowered. Try the effect of gradually turning the plate round to a position at right angles to the lines. Result?

Continue the lines AB and EF to the lines representing the surfaces of the plate, and draw a straight line (between the parallel lines of CD) joining their extremities. The broken line $ABEF$ now represents the path of a ray of light passing obliquely through the plate. Place an arrowhead on each part of the broken line. Produce FE as a dotted line to represent the apparent position of AB , when viewed through the plate.

b. Stand the prism on end on a page of your note book, with its rear face at an angle of about 45° with a line AB (Fig. 75); and, as with the glass plate, draw a line FG in front of the prism and in line with the apparent position of AB as seen through the prism. Draw the outline of the base of the prism, and complete the construction, showing the path of a ray of light through the prism. Produce GF backward as a dotted line to represent the apparent position of AB . Draw perpendiculars to CD and ED at the points of entrance and emergence of the ray; letter the two angles of incidence i , the two angles of refraction r , and the angle of total deviation d (the acute angle between AB and FG produced).

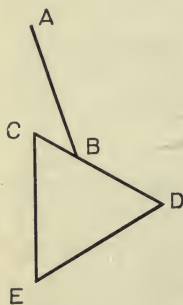


FIG. 75.

c. Hold the glass plate up before you with your pencil behind it, both vertical, and the plate turned obliquely to the line of sight. Compare the apparent position of the pencil, viewed thus obliquely through the glass, with its real position, as shown by the upper end of it, viewed above the plate. Move the pencil to a distance of a foot or more back of the plate, and observe whether the distance between its real and apparent positions changes.

d. Repeat with the prism in place of the plate. In moving the pencil away from the prism, move it in such a direction that it

continues visible through the prism. Compare the results with those obtained with the plate, and account for the difference.

e. Look at any distant straight lines, as the outline of a building, through a common window pane, and note their apparent wavy distortion. Observe their apparent wriggling motion as the head is moved from side to side. Explain.

Experiment 95. — *To study phenomena due to total reflection in glass and in water.*

Apparatus. — Triangular glass prism with flat ends; glass jar, preferably rectangular; large jar of water; beaker; rule; mop cloth.

Experimental Work. — *a.* Lay a glass prism down on a side on a printed page. Look at the page through the prism, with the eyes at first directly above it. Slowly lower the head so as to view the page more and more obliquely through the near side of the prism until the printing is no longer visible. Describe and account for the appearance of the lower face of the prism and the disappearance of the printing, referring to a copy of Figure 76. Remember that there is a thin layer of air between the prism and the paper.

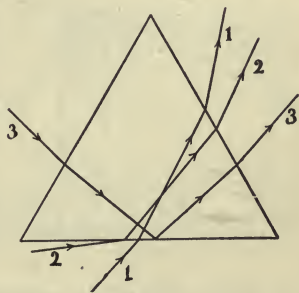


FIG. 76.

b. With the eyes in such a position that the printing is invisible, test the reflecting power of the lower face of the prism by viewing in it the image of your pencil, held near the farther face of the prism. While still viewing this image, slowly raise the head till the printing becomes visible, and note the change in the brightness of the image. Explain.

c. Moisten a part of the lower face of the prism with a drop of water on the finger, and press this face down on the printed page. Can the printing be seen through the moistened part of

the surface when the eyes are in position to receive total reflection from the remainder of it? Find whether there is total reflection from the moistened part of the surface at any angle. With the eyes in position to see the printing through the moistened part of the surface but not through the remainder, observe the gradual disappearance of the printing as the moisture is absorbed by the paper.

In this experiment water takes the place of air between the paper and the moistened part of the lower face. From the observed phenomena do you find the critical angle at a glass-water surface greater or less than at a glass-air surface?

d. Stick a bit of gummed paper on the outside of the smaller jar 5 or 6 cm. from the top. Fill the jar level full of water, and

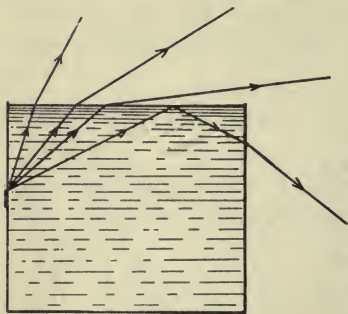


FIG. 77.

stand it near the edge of the table with the bit of paper on the side opposite you. Look at the paper through the surface of the water, while gradually lowering the eyes till they are on a level with the surface, and note the continuous change in the apparent position of the paper. Continue to lower the head while looking upward through the side of the jar at

the under side of the surface of the water. Presently an image of the paper will be seen by reflection in this surface. Copy Figure 77 and finish it, showing the position of the image of the paper for different positions of the eye. Why does the image by reflection not appear as soon as the eyes are too low to see it by refraction through the surface of the water?

e. With the eyes directed upward toward the surface of the water, observe in it the image of your pencil, held partly under water. What evidence is there that this image is formed by total reflection?

EXERCISE 51. THE CONVEX LENS

References. — Adams, 318–326; Coleman, 374–379; Car. & C., 269–274; Ches. G. & T., 321–329; Hoad. Br., 477–480, 483–484; Hoad. El., 525–528, 530–532; Mumper, 204–206; Mil. & G., 546–549; Went. & H., 386–388, 390.

Experiment 96. — *To find the focal length of a convex lens; and to study the formation of real and virtual images by it.*

Apparatus. — Meter rod; mounted lens, having a focal length of 10 to 15 cm.; two mounted cardboard screens, one having a circular hole about 5 cm. in diameter at the same height as the lens; mounted candle.

[Various inexpensive supports for lenses are supplied by dealers. Figure 78 shows very satisfactory metal supports for lens and screen. The support for the lens should have a neck, as shown

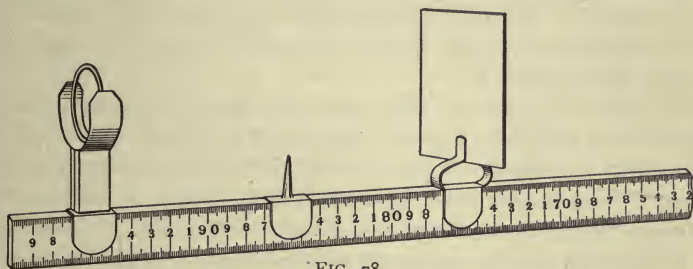


FIG. 78.

in the figure, to hold the lens several centimeters above the meter rod. This is much more convenient than to have the lens down on the rod. Figure 79 shows another form of support, consisting of a wooden block and upright strips of brass.]

Experimental Work. — *a.* Place the lens at about the middle of the meter rod, and turn it toward some distant object, visible through an adjacent window. If it is not too cold, open the window, to avoid the unequal refraction of the glass. Place the screen with the hole close behind the lens (*i.e.* on the side oppo-

site to the object). Place the other screen back of the first, and adjust its distance so that a distinct image of the distant object is focused on it. The screen with the hole is to intercept as much of the light from other sources as possible. Note the effect of removing it.

Measure the distance from the lens to the image. (If the lens and screen are mounted at the middle of blocks of the same length, take the readings of the meter scale at corresponding ends of these blocks, and subtract one from the other.) This distance is the focal length f of the lens.

b. Remove the screen on which the image is focused, and stand the other screen in its place, so that the image will be in the air in the hole of this screen. Place the head a foot or two back of the screen, and look at the image with both eyes, focusing them on the hole (*not* on the more distant lens). The screen serves merely as an aid in focusing the eyes on the real position of the image. You may succeed without it, though this is difficult for the beginner. If not quickly successful in trying to view the image directly, pass it.

c. Take the apparatus to a darkened corner of the room, or, better, to a room where all the shades can be drawn. Place the lens near the middle of the rod and the lighted candle at one end. Focus the image of the candle on the screen to determine its position, then remove the screen and view it directly. Observe the change in the size and position of the image (either viewing it directly or focusing it on the screen) as your companion slowly carries the candle from its present position to a distance of several meters. Repeat a number of times, comparing roughly the distances through which the candle and the image move. Does the position of the image change more or less rapidly for a given motion of the candle as the distance of the candle becomes large?

Measure the distance of the image from the lens when the candle is at its greatest distance, and compare with the focal length of the lens. What point would the image approach if the distance of the candle were increased indefinitely?

d. Move the candle slowly toward the lens from a distance of about half a meter, and follow the change in the size and position of the image, by focusing it on the screen. Does it move more or less rapidly than the object?

Focus the image, if possible, on a distant wall of the room, and measure the distance of the candle from the lens. Compare this distance with the focal length. What would become of the image if the candle were moved up to the principal focus?

e. Place the eye close to the lens and look through it at the candle, and observe the change in its apparent size and position as you move it toward the lens from a position beyond the principal focus. What appears to be the "magnified candle" is the magnified virtual image of the candle.

f. Standing in a well-lighted part of the room, hold the lens in one hand at a distance of about 30 cm., and hold your pencil close behind it. Look with both eyes through the lens at the image of the pencil, and compare its size and position with the part of the pencil seen above the lens, as you slowly move the pencil back from the lens. Continue the observation as you move the pencil back and forth through the whole distance within which the image remains distinct. If you have difficulty in seeing the image in its true position, keep the eyes steadily on it as you start with the pencil close to the lens and move it slowly back. A slight shifting of either the lens or the pencil from side to side is also helpful. Find from these observations the answers to the following questions : —

Is the distance of the image ever greater than that of the object? Is it always greater? Which increases more rapidly, the distance of the object or the distance of the image?

How does the size of the image change as the object is moved back from a position close to the lens?

What is the greatest distance of the object at which the image remains distinct? (Measure it and compare with the focal length of the lens.) Why is the image indistinct when the object is at a greater distance than this?

Discussion. — From the results of the experiment, together with a study of the text, find answers to the following questions : —

1. What happens after refraction to the diverging cone of light that falls upon the lens *from any one point* of the object, (*a*) when the distance of the object is greater than the focal length? (*b*) less than the focal length? (*c*) equal to the focal length?

2. What behavior of the refracted light results in (*a*) a real image? (*b*) a virtual image?

3. (*a*) Under what conditions is a real image formed? (*b*) a virtual image?

4. With rule and compass draw accurate figures showing the size and position of the image in the following cases. Use the same focal length in all the figures, and in all but the first an arrow of the same length as object. The object cannot be represented in the first figure. (Why not?)

Object large and at a relatively great distance (illustrating paragraph *a*).

Distance of object greater than twice the focal length (illustrating paragraph *c*).

Distance of object greater than the focal length and less than twice the focal length (illustrating paragraph *d*).

Distance of object slightly less than the focal length, and also when only a small fraction of the focal length (illustrating paragraph *f*).

EXERCISE 52. CONVEX AND CONCAVE LENSES

References. — Adams, 319-327; Coleman, 380, 382; Car. & C., 271-274; Ches. G. & T., 330; Hoad. Br., 481-482; Hoad. El., 525-532; Mumper, 206-207; Mil. & G., 550-551; Went. & H., 386-390.

Experiment 97. — *To find the focal length of a convex lens from its relation to conjugate focal distances; and to compare the relative size of image and object with their respective distances from the lens.*

Apparatus.— Lens of 10 to 15 cm. focal length; meter rod; two mounted screens, one having a round hole about 1 in. in diameter, with cross wires (Fig. 79); flat gas jet or lamp.

Experimental Work.— Find the focal length f of the lens by focusing the image of a distant object on a screen, as in the preceding exercise.

Draw the window shades, at least those near the apparatus, so as to make the room rather dark. Stand the screen with the

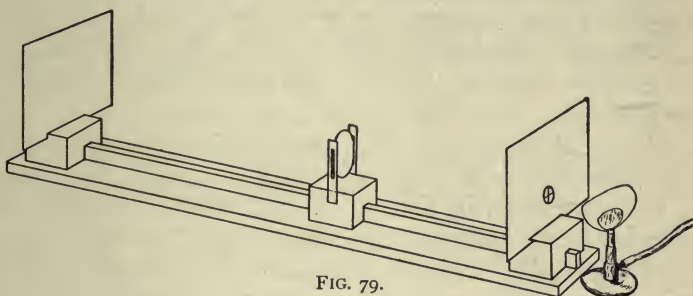


FIG. 79.

cross wires at an end of the rod, and turn the gas jet flatwise toward it. Place the lens at a distance exactly equal to twice its focal length from this screen, and adjust the other screen so that the image of the cross wires is exactly focused upon it. The image of the cross wires may be red, black, or greenish blue, depending upon the position of the screen. Adjust for a black image. Let p denote the distance from the lens to the cross wires, and p' from the lens to the image. Record as indicated below. Measure carefully the diameter of the hole containing the cross wires and the diameter of the image. Call the first the length of the object l , and the second the length of the image l' .

Move the screen on which the image is caught to the farther end of the rod; then move the lens toward the cross wires till the image is again distinct on the screen. Measure p , p' , and l' .

Without changing the position of either screen, move the lens away from the cross wires till the image again falls upon the other screen; and measure p , p' , and l' .

Data and Computations.—Consult the text-book for the derivation of the lens formula $1/p + 1/p' = 1/f$. Solved for f , this gives $f = pp'/(p + p')$. The average of the three values of f computed from this formula is the focal length of the lens as found by the method of conjugate foci. Compare this with the value obtained by focusing on a distant object.

Consult the text, also, for the geometrical proof that the true values of the ratios p'/p and l'/l are equal. Write all ratios in the tabulated record as quotients expressed decimally. Record as follows:—

p	p'	$\frac{pp'}{p+p'}$	l'	p'/p	l'/l	DIFFERENCE $p'/p - l'/l$	PER CENT OF DIFF.
— cm.	— cm.	—	—	—	—	—	— %
— cm.	— cm.	—	—	—	—	—	— %
— cm.	— cm.	—	—	—	—	—	— %

Focal length of lens f found by focusing on a distant object = cm.

Average value of focal length, computed from conjugate focal distances = cm.

Percentage of difference between focal lengths by the two methods = %.

Diameter of circular hole (length of object) l = cm.

Discussion.—*a.* Show from the formula that p and p' should be equal in the first set of measurements.

b. How do p and p' of the second set of measurements compare with p' and p respectively of the third set? What principle of conjugate foci is illustrated by these two pairs of values?

Experiment 98. — *To study the formation of images by a concave lens.*

Apparatus. — Concave lens.

Experimental Work. — *a.* Try to focus a beam of sunlight on a sheet of paper with the concave lens, as you do with a convex lens. State and account for the result.

b. Hold the lens up before a window (preferably open) at a distance of a foot or more from the face, and look through it with both eyes at the image of distant objects. Shift the lens slightly from side to side to aid in locating the image. The distance of the image is the focal length of the lens. Estimate this distance as closely as you can.

c. Look at nearer objects through the lens, — as the window, the floor, a page of your book, your hand, a pencil, etc., — always with both eyes and with the lens a foot or more from the face. Compare the relative size and distance of object and image in each case. As the object approaches the lens, what change takes place in the size and position of its image? Where is the image when the object is close to the lens?

Draw three diagrams showing the formation of an image by a concave lens; the first with a large object at a relatively great distance (the object not shown in the figure); the second with the object (represented by an arrow) at about twice the focal length; the third with the distance of the object about one fourth the focal length. Take the same focal length in the three diagrams.

EXERCISE 53. THE EYE

(INVENTIVE)

References. — Adams, 331-333; Coleman, 383-386; Car. & C., 301-302; Hoad. Br., 520-521; Hoad. El., 570-572; Mumper, 215; Mil. & G., 555; Went. & H., 403-404.

Experiment 99. — *To study the structure of the eye by means of a dissected model.*

Apparatus. — A large anatomical model of the eye, separable.

Suggestions. — Examine the model in connection with the study of the text and any school physiology on the subject of the eye. Handle the model only with clean hands and as little as will serve the purpose, to avoid unnecessarily soiling it. Make note of any points not fully understood, and bring them up for discussion in the recitation. The parts of the eye, their appearance, shape, relative position, physical properties, structure, and function should all receive attention, primarily from the point of view of the eye as an optical instrument.

Experiment 100. — *To examine a dissected eye of an ox.*

Material. — An ox's eye, dissected by the teacher.

Suggestions. — If several pupils are to study the same eye, it should be disturbed but little. At the most, use the scalpel or other dissecting instrument to move the parts slightly, if necessary to get a good view of them, or to test their texture, rigidity, etc. Examine the specimen closely in connection with a study of the text or any physiology.

EXERCISE 54. THE SIMPLE AND THE COMPOUND MICROSCOPE

References. — Adams, 335-336; Coleman, 393-395; Car. & C., 295-296; Hoad. Br., 513-514; Hoad. El., 562-563; Mumper, 206, 211; Mil. & G., 556-558, 560; Went. & H., 406, 411-412.

Apparatus. — Two mounted lenses, preferably of equal focal length not over 10 cm.; meter rod; two small mounted screens with printing and metric scale.

[Lenses and screens mounted as in Figure 78 are preferable. The screens are better small — not over 6 by 8 cm. Printing in the same size of small type is pasted on one side of each screen and a paper metric scale 5 cm. long at the left edge of the other side. The screens should be held in their supports only by the pressure of the springs, so that they can be shifted to right or left.]

Experiment 101.—*To find the magnifying power of a simple microscope.*

Experimental Work.—*a.* Place a lens at an end of the meter rod, and adjust one of the screens back of it so as to read the fine printing with one eye, placed close to the lens. Estimate the magnification.

b. Place both of the screens behind the lens on the rod, with the metric scales turned toward the lens, and the farther screen at a distance of 25 cm. from the lens. Adjust the nearer screen so that the scale is distinctly seen through the lens, with the eye close to it.

With the screens remaining at these distances and the scales at the left side of each (invert if necessary), shift the nearer screen to the right until the scale is directly over the meter rod. Look at this scale with the right eye, placed close to the lens, and at the same time look through the air with the left eye at the farther scale. While looking thus with both eyes, slip the farther scale to the left till it appears to the left and close beside the image of the nearer scale. (If you prefer to look through the lens with the left eye, read right instead of left, and *vice versa*, in the above directions.) If you have difficulty in seeing both scales distinctly at the same time, winking with one eye or the other, or both, will help. Note as accurately as possible the length on the farther scale that is equal to a centimeter on the magnified image of the nearer scale.

This gives the magnification produced by the lens when used to the best advantage as a simple microscope. For example, if the magnified centimeter has the same length as 2 cm. on the scale which is viewed with the naked eye at 25 cm. (the least distance of distinct vision), the magnification is 2.

c. Compare the magnification, thus determined, with the ratio of the distance of the farther screen (25 cm.) to the distance of the nearer screen from the lens. Record the latter distance as well as the ratio.

d. Find the focal length of the lens f by focusing it on a distant object. Compute the ratio of 25 cm. to the focal length. This ratio ($25/f$, the distances being measured in centimeters) is the formula for computing the approximate value of the magnification from the known focal length (see text).

Oral Discussion. — 1. Is the ratio determined in *c* or in *d* more nearly equal to the magnification as determined by direct comparison?

2. Which should you expect to be more nearly equal, and why?

Experiment 102. — *To adjust and use a pair of lenses as a compound microscope; and to determine the magnification.*

Experimental Work. — *a.* Leave the lens that you have been using at the end of the rod, to serve as the eye lens. Place the other lens (the objective) on the rod at a distance of four or five times the focal length from the first. (The two lenses are of equal or nearly equal focal length.) Place one of the screens beyond the objective, with the printing turned toward you; and adjust its distance so that the printing is distinct when viewed through the two lenses. Probably not more than two or three letters will be visible, the field of view being very small. Note the distortion and coloring of the image. These imperfections and their remedy are discussed in the text. The image will appear greatly magnified in comparison with the printing viewed directly with the other eye at that distance (50 to 60 cm. with lenses of 10 cm. focal length); but the correct comparison is made with the printing as it appears to the unaided eye *at a distance of 25 cm.* The metric scales will be used for this purpose in the work of the next paragraph.

b. Reverse the screen, and slip it to right or left till as much of the scale as possible is distinctly visible through the lens. Hold the other screen in the hand 25 cm. from the eye lens and in such a position that the scale on it, viewed directly with one eye, appears close beside the image of the farther scale, viewed through the lenses with the other eye. From a comparison of the scales,

determine the magnification. For example, if 2 mm. of the magnified scale appear as long as 9 mm. on the other, the magnification is $9/2$, or 4.5.

c. Measure the distance between the lenses and the distance from the objective to the screen used as object.

Let p denote the latter distance (represented by AO in Figure 80) and p' the distance from the objective to the real image formed

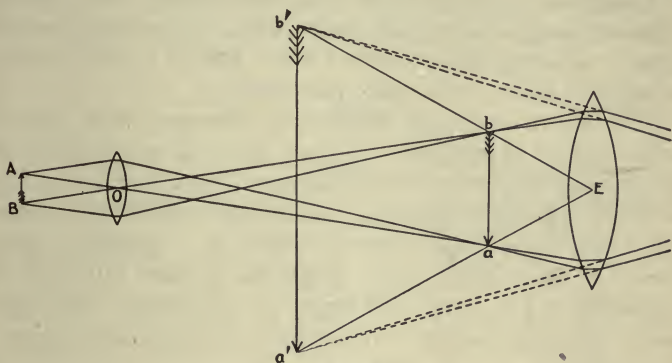


FIG. 80.

by it (Oa in the figure). This real image ba is approximately at the principal focus of the eye lens (really at a somewhat less distance from the eye lens, as an object would be when viewed through the eye lens alone); hence the approximate value of p' is found by subtracting the focal-length of the eye lens from the distance between the lenses.

Since p and p' are conjugate focal distances, the magnification due to the objective alone is p'/p . The magnification due to the eye lens is the same as when that lens is used alone, its approximate value being $25/f$. Hence the magnification due to objective and eye lens together is $p'/p \times 25/f$. Compute the magnification from this formula, and compare with the value found by direct observation.

Record data and computations in the usual form.

EXERCISE 55. THE ASTRONOMICAL AND THE GALILEAN TELESCOPE

References.—Adams, 337–338; Coleman, 396, 398; Car. & C., 297–298; Hoad. Br., 515–517; Hoad. El., 564–566; Mumper, 212, 214; Mil. & G., 559, 562; Went. & H., 413–415.

Apparatus.—Convex lens of long focal length; two convex lenses of unequal short focal length; concave lens of short focal length; two mounted screens, one with a hole of 1.5 in. diameter at height of lenses; meter rod; metric rule.

[The lenses commonly supplied for laboratory work have a focal length of 10 to 15 cm. If these are used as eye lenses in this experiment, the objective should have a focal length of 40 cm. or more; but a diameter of 4 cm. is quite sufficient. Dealers will supply such lenses, made to order, at a moderate price. Lenses of 15 to 16 cm. focal length can be used as objectives with lenses of 3 to 8 cm. focal length for eye lenses. The latter can be obtained, mounted in various ways, as simple microscopes.]

Experiment 103.—*To adjust and use a pair of lenses as an astronomical telescope; and to determine the magnification.*

Experimental Work.—*a.* Find the focal lengths of the three convex lenses by focusing on a distant object. The screen with the hole, placed just back of the lens to cut off diffused light, will probably not be sufficient to make the image visible with the lens of long focal length, as the image is large and correspondingly faint. Lower the window shade nearly to the level of the table, and stand before the window so as to cut off light from the side as much as possible. Let f_1 denote the greatest focal length, f_2 the next, and f_3 the shortest. The lenses will be referred to as lens f_1 , lens f_2 , and lens f_3 .

b. Place lens f_3 as eye lens at an end of the meter rod, and lens f_1 as objective at a distance from the first, approximately equal to the sum of their focal lengths. Turn the telescope thus formed

toward a distant object ; and, with the eye close to the lens, adjust the objective till the image is distinct. The window should be raised if the weather will permit. Note the border of color round the edges of objects. Is the color stronger when you look through the centers of the lenses or through their marginal portions? This defect and its remedy is discussed in the text under *chromatic aberration* and *achromatic lenses*.

c. Turn the telescope toward a distant chimney, tower, water tank, or other regular object of moderate size. A window will

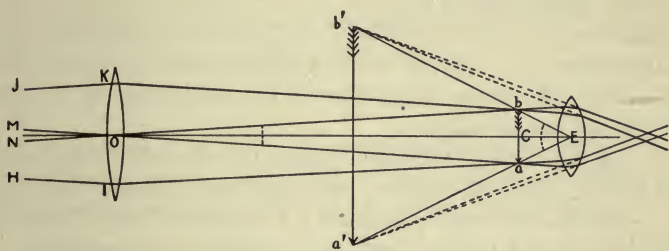


FIG. 81.

serve, or a letter of a large sign ; but an isolated object having the sky as a background is much the best. Support the meter rod upon books or blocks, or with a stand and clamp, so that it can be pointed steadily toward the object. While looking at the object directly with one eye and through the telescope with the other, turn the telescope so that the image directly overlies the object, and estimate the magnification.

d. Measure the distance between the lenses. This is the length l of the telescope.

e. Repeat the above work with the same objective and lens f_2 as the eye lens ; and again with lens f_2 as the objective and lens f_3 as the eye lens.

Data and Computations. — Compare the estimated magnification in each case with the ratio of the focal length of the objective to the focal length of the eye lens. Compare also the length of

the telescope with the sum of the focal lengths of objective and eye lens. Record as follows : —

Focal length $f_1 =$ cm., $f_2 =$ cm., $f_3 =$ cm.

ESTIMATED MAGNIFICATION	COMPUTED MAGNIFICATION	DIFFERENCE	l	SUM OF FOCAL LENGTHS	DIFFERENCE
—	$f_1/f_3 =$ —	—	— cm.	$f_1 + f_3 =$ —	—
—	$f_1/f_2 =$ —	—	— cm.	$f_1 + f_2 =$ —	—
—	$f_2/f_3 =$ —	—	— cm.	$f_2 + f_3 =$ —	—

Discussion. — 1. Discuss the first and second combinations of lenses as an illustration of the effect of the focal length of the eye lens on the magnification.

2. Discuss the first and third combinations as an illustration of the effect of the focal length of the objective on the magnification.

3. Discuss the relation between the lengths of the telescopes and the sum of the focal lengths of the objective and eye lens.

4. Copy Figure 81 and answer the following questions : —

a. Which rays come from a point at the top of the object, and which from a point at the bottom?

b. What (in the figure) is the focal length of the objective? of the eye lens?

c. What is the visual angle with the naked eye? with the telescope?

d. What ratio (of lengths) measures the magnification?

Experiment 104. — *To adjust and use a convex and a concave lens, as a Galilean telescope; and to determine the magnification.*

Experimental Work. — *a.* To find the focal length of the concave lens, hold it about a foot from the face, look through it with both eyes at the image of a distant building, and measure with the rule the distance between the image and the lens. In doing this, look at the farther end of the rule directly (not through the lens), and extend it just to the image. (The method is similar to

that of finding the apparent width of a glass plate or the apparent depth of water in a vessel.)

b. Place the concave lens at the end of the meter rod. This is the eye lens. Use the lens of long focal length f_1 as the ob-

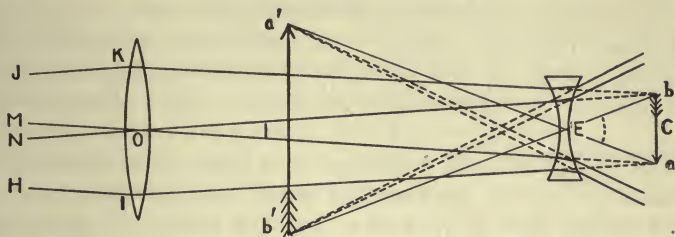


FIG. 82.

jective, and place it at the greatest distance from the eye lens that will give a distinct image of a distant object. Estimate the magnification and measure the distance between the lenses.

Discussion.—1. Compare the length of the telescope with the difference between the focal lengths of the lenses.

2. Compare the estimated magnification with the ratio of the focal length of the objective to that of the eye lens.

3. Copy Figure 82 and answer the questions under 4 of the discussion at the end of the preceding experiment.

EXERCISE 56. THE SPECTRUM; COLOR

References.—Adams, 277-280, 286-291, 299-300; Coleman, 401, 403-404, 407-408, 410, 419; Car. & C., 277-278, 287-289, 291-293; Ches. G. & T., 331-332, 339, 341-352; Hoad. Br., 486-487, 494-496, 498-499, 508-509; Hoad. El., 534-536, 543-546, 556-557; Mumper, 209, 217-221; Mil. & G., 565-574; Went. & H., 392-394, 417-418, 422-425.

Experiment 105.—*To determine by analysis with a prism the elementary or prismatic colors of sunlight, of light transmitted through colored glass, and of light reflected from colored surfaces.*

Apparatus. — Prism of flint glass ; square of black cardboard (Fig. 83) with a slit 1 mm. by 2 cm. and a slit 1 cm. by 2 cm. ; pieces of colored glass 3 to 5 cm. square ; strips of colored paper 1 mm. wide and 2 cm. long, pasted on black cardboard.



FIG. 83.

[A prism of crown glass will serve, but flint glass gives nearly twice the dispersion, which is an advantage. Pieces of cardboard 10 or 12 cm. square serve for the slits and the strips of colored paper. For these strips use white and several of the spectrum colors ; and arrange them on the card so that their spectra can be easily distinguished from one another. The squares of colored glass should include ruby, yellow, and blue. The ruby is a fine example of a nearly pure spectrum color. The yellow and blue should be selected to give bright green by transmission through both.]

Experimental Work. — *a.* Stand facing a window, and hold the cardboard with the slits out nearly at arm's length, with the slits horizontal and strongly illuminated by sunlight (having the sky for a background). Look at the narrow slit through the prism, held close to the eye with its long edges horizontal and its faces turned, as shown in Figure 84. Looking obliquely down at an angle of about 35° to the direction of the slit, you will see the overlapping colored images of it which together constitute the spectrum of sunlight. Copy Figure 84 on a large scale, and mark by the initial letters *R*, *O*, *Y*, etc., the colors of the spectrum in the observed order. What color is refracted most? what least?

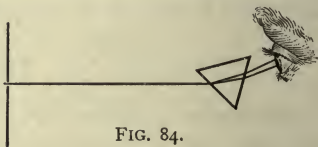


FIG. 84.

b. Look at the wide slit in the same way. Record the colors in their observed order in a figure similar to Figure 84, but with a wide beam of light represented instead of a ray. The figure

should account for the fact that the central portion of the slit appears white. Explain.

c. Cover one end of the narrow slit with the blue glass, and view the slit with the prism, as before. You now observe side by side the complete spectrum and the spectrum of the light that is transmitted through the blue glass. What colors besides spectrum blue are transmitted by the glass? The colors not transmitted are absorbed. Record as shown below, designating the colors by initials.

Make a similar analysis of the light transmitted by the yellow glass, by the blue and yellow together, and by the other pieces provided.

COLOR OF GLASS	COLORS TRANSMITTED	COLORS ABSORBED
Blue		
Yellow		
Blue and yellow		
Red		
Etc.		

d. Look through the blue and yellow pieces of glass placed together (not using the prism), and note the color. Explain.

e. Hold the colored strips on the cardboard in a strong light (direct sunlight, if possible), and analyze with the prism the light reflected by them. Record in tabular form, as in paragraph *c*, heading the first column "color of the strip," the second "colors reflected," and the third "colors absorbed." Colors that appear very faint in the spectrum are to be recorded as absorbed.

Experiment 106. — *To determine the color resulting from the synthesis (union) of various colored lights; and to distinguish complementary colors.*

Apparatus. — Several pieces of black cardboard on each of

which are pasted two squares of colored paper (Fig. 85); piece of window glass about 6 by 10 cm.

[On pieces of black cardboard about 8 by 12 cm., paste colored papers 4 or 5 cm. square, two on each card, close together.

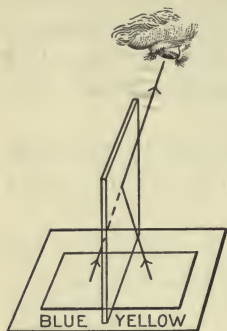


FIG. 85.

Some of these pairs of colors are to be complementary, others not. Any of the following are good: blue and yellow, red and bluish green, green and purple, violet and yellowish green, red and yellow, green and violet, violet and red, orange and green.]

Experimental Work.—Stand the piece of window glass between the yellow and blue squares on one of the cards, with the yellow color toward you, as shown in Figure 85. Look through the glass at the blue square. Superposed on it will be an image of the yellow square, due to partial reflection from the window glass; and the blue paper will appear to be of the color it would have if all the light that enters the eye from its direction actually came from it. Inclining the glass forward increases the amount of reflected yellow light and decreases the amount of transmitted blue light, causing the appearance of the blue paper to change from blue through white or light gray to yellow. Inclining the glass backward produces the opposite effect. Observe the nearest approach to white that can be obtained in this way.

Repeat the experiment with the red and yellow papers. (It is immaterial in any case which paper is in front.) An intermediate white or gray is impossible in this case. What color is produced instead?

Try in the same way all the pairs of colors provided. Name in one group all those pairs of colors which, like the blue and yellow, give white or gray. All such pairs are *complementary colors*. Record the component and resultant colors in tabular form.

Discussion. — 1. Compare all results with the arrangement of colors shown in Figure 86, and state the results in general terms with reference to this arrangement.

2. How is it possible that the yellow and blue pieces of glass together transmit green, while the light from the yellow and blue papers gives white when combined?

Experiment 107. — *To study the production of color by interference.*

Apparatus. — Two pieces of thick plate glass; small iron clamp; soap-bubble solution in a jar; wire loop with handle.

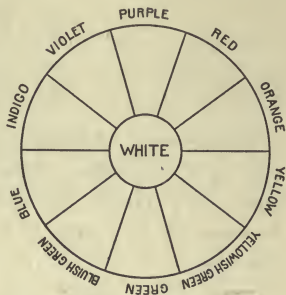


FIG. 86.

Experimental Work. — *a.* Clamp the two pieces of glass firmly together, being careful to have the surfaces that are in contact thoroughly clean. Hold them in a strong light, and look at them from the illuminated side. Observe the curved bands of spectrum colors which surround the spot where the clamp is applied. Account for them after consulting the text.

How do these bands of colors change as you apply additional pressure at the edges of the plates with the fingers? How do they change as you turn the plates about and view them at different angles? Explain.

b. Cover the wire loop with a film of the soap solution, and hold it in a strong light, with the film vertical. Note the gradual appearance of bands of color in the upper side of the film. These interference colors are due to the gradual thinning of the upper part of the film under the action of gravity. Describe.

X. MAGNETISM

EXERCISE 57. MAGNETS AND MAGNETIC ACTION

References.—Adams, 436-443, 449-451; Coleman, 420-428; Car. & C., 358-369; Ches. G. & T., 354-359; Hoad. Br., 291-298, 307; Hoad. El., 326-336, 345-346; Mumper, 222-228; Jackson, 68-83; Mil. & G., 305-311; Went. & H., 240-243, 245-246.

Apparatus.—Bar magnet; magnetic needle on stand (Fig. 87); coarse iron filings or very small tacks in a box longer than the magnet; small pieces



FIG. 87.

of various substances, as iron, steel, brass, copper, lead, glass, paper, etc.; pieces 8 or 10 cm. square of cardboard, glass, thin

wood, sheet iron (or tin), zinc, lead, and brass; rods of soft iron, steel (knitting needle), and brass or wood of equal length (15 to 20 cm.).

Experiment 108.—*To determine the distribution of attracting power in a magnet, the polarity of a magnet, and the law of magnetic action.*

Experimental Work.—*a.* Lay the magnet in the box of iron filings, so that its whole length comes in contact with the filings. Lift the magnet and observe the distribution of the filings that cling to it. Draw a sketch to illustrate. The regions where the power of attraction is greatest are called *poles*. Is there any evidence of attraction at the center? Remove the filings by wiping them toward the middle of the magnet.

b. Test the attracting power of the magnetic needle (Fig. 87) in the same way. (Do not let it come in contact with the bar magnet.) The needle is a magnet adapted in its form to special uses. Replace it on its stand.

c. Remove all magnetic substances to a distance not less than a meter from the magnetic needle, and observe its behavior when disturbed and free to turn on its support. Does it always come to rest with the same end pointing in the same direction? The end that points north in the position of equilibrium is called the *north pole*. Note its color (commonly blue), which serves to distinguish it from the *south pole*.

The bar magnet, if supported so as to be free to turn in a horizontal plane, would behave like the needle.¹ The end that would point north is marked N. The south pole is sometimes marked S, sometimes left unmarked.

d. Observe the effect of bringing each of the poles of the bar magnet near each of the poles of the magnetic needle. What action is observed between like poles? between unlike poles? Remember that the action between two bodies is always mutual (Newton's third law). Is there any evidence of action on the bar magnet? Why or why not? If not, can you suggest any means by which it might be detected?

e. Note roughly the rapidity of vibration of the magnetic needle when removed from all magnetic substances and disturbed from the position of equilibrium. Note the change in the rate of vibration as a pole of the bar magnet is slowly brought up toward the unlike pole of the needle. The increased rate indicates increased magnetic force. It can be shown mathematically that the magnetic force acting on a needle is proportional to the square of its rate of vibration. Thus, if the rate increases to twice its original value, we know that the magnetic force is four

¹ It will not serve in testing this to suspend the magnet by a thread, for the tension on the thread causes it to untwist with a force that is commonly greater than the magnetic force that tends to set the magnet north and south. An untwisted fiber should be used for the suspension.

times as great as at first. The more or less rapid vibration of the magnetic needle often serves to indicate roughly the relative magnitude of magnetic forces. It is unnecessary in elementary physics to measure them.

What do your observations indicate concerning the effect of distance from a magnet on the magnetic force exerted by it.

Experiment 109.—*To distinguish magnetic and nonmagnetic substances; and to determine which of these act as magnetic screens.*

Experimental Work.—*a.* Find which of the small pieces of various substances provided are attracted by a magnet, and which are not. Classify the former as magnetic and the latter as non-magnetic.

b. Put a small quantity of iron filings (or tacks) on the cardboard, and move a pole of the magnet about against the under side of the cardboard beneath the filings. What evidence is there of magnetic action through the cardboard? Repeat with the piece of sheet iron in place of the cardboard, and try all the substances provided in the same way. Classify them in two groups according as they do or do not act as a screen to cut off magnetic action. What relation do you find between this classification and that of magnetic and nonmagnetic substances?

Gather up with the magnet any scattered filings.

c. Hold a pole of the bar magnet about 1 cm. from the unlike pole of the magnetic needle, and note the rate of vibration. Slip the piece of sheet iron between, and observe the effect on the rate of vibration. Conclusion? Try the other substances in the same way.

Experiment 110.—*To study phenomena of magnetic induction.*

Experimental Work.—*a.* Find whether the soft iron rod attracts iron filings. Try again with an end of the magnet against the upper end of the rod. What happens to the load of filings on the end of the rod when the magnet is removed from the other end? What does this indicate concerning the magnetic condition of the rod?

b. With an end of the bar magnet against an end of the soft iron rod, test the polarity of the other end of the rod by bringing it up to the magnetic needle. Is this pole like or unlike the pole of the magnet which is in contact with the other end of the rod? With the rod still in place, reverse the magnet, bringing its other pole in contact with the rod, and note the effect on the needle.

The iron rod is itself a magnet while in contact with the bar magnet, and has two unlike poles. You have tested one of these poles, and hence by inference know the other. Is the pole of the rod at the end touched by the magnet like or unlike that with which it is touched? Draw a figure showing the arrangement of poles in the magnet and the rod, when they are placed end to end.

c. Repeat the work of paragraph *a* with the steel rod. Do you find it already magnetized? If so, how do you account for this condition? Determine its polarity by testing with the magnetic needle. Find whether the polarity of one end of it is reversed by merely changing the pole of the magnet with which its other end is touched. If not, find whether you can reverse its polarity by repeatedly rubbing it from the center to one end with one pole of the magnet, and from the center to the other end with the other pole. Are the poles of the rod like or unlike the poles of the magnet that were applied to produce them?

d. Test the brass (or wooden) rod as you did the iron rod in *a* and *b*. In repeating *b*, hold a pole of the magnet so that the distance between it and the needle is a little greater than the length of the rod, and observe whether interposing and removing the brass rod between them has any effect on the needle. Try the same with the iron rod.

Does a nonmagnetic substance in the form of a rod affect magnetic action? Does it in the form of a sheet (Exp. 109, *b*)? Compare the effects of a magnetic substance in the two forms. In this connection make a further test of the sheet iron by holding an end of the magnet against its center, while touching its edge to iron filings.

EXERCISE 58. MAGNETIC FIELDS

References. — Adams, 452-455 ; Coleman, 431-432 ; Car. & C., 374-377 ; Ches. G. & T., 363-367 ; Hoad. Br., 299-300 ; Hoad. El., 334-337 ; Mumper, 230 ; Jackson, 84-90 ; Mil. & G., 312-314 ; Went. & H., 249-251.

Apparatus. — Two bar magnets ; small compass ; board about

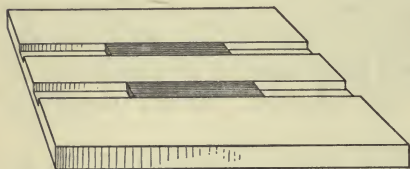


FIG. 88.

10 by 15 in. with parallel grooves about 2 in. apart, in the direction of the length (Fig. 88) ; one or more pieces of thick cardboard 9 by 11 in. ; fine iron filings in pepper box or other sifter ; with or

without blue-print paper and rubber bands to fasten it to the cardboard.

Experiment 111. — *To determine the shape and direction of the lines of force in the magnetic field about a bar magnet.*

Experimental Work. — *Without Blue-print Paper.* Place a magnet in one of the grooves of the board, and note the position of its north and south poles. Lay the cardboard over the magnet, and sprinkle iron filings thinly and evenly over it from the height of about a foot. Gently tap the cardboard at different points with the finger (not the finger nail), while holding it in place. The slight jarring helps to overcome friction, and enables the filings to arrange themselves in lines under the action of the magnet.

Place the compass at different points about the magnet, and compare the direction of the needle in each position with the direction of the lines of filings at that place. The lines of filings are more or less irregular and broken ; the *magnetic lines of force* which they imperfectly sketch are really smooth, continuous curves. Draw a diagram on a reduced scale, representing the magnet and several lines of force about it, as indicated by the lines of filings.

Mark the poles of the magnet N and S. Be careful to represent the position and curvature of the lines of force, as correctly as possible, by regular, unbroken lines. Place an arrowhead on each line, indicating the direction along the line in which the north pole of the compass needle points.

With Blue-print Paper. — Fasten a sheet of the blue-print paper, prepared side up, to the cardboard by means of rubber bands, and proceed as above, sprinkling the filings on the blue-print paper and omitting the pencil sketch. *Keep unused blue-print paper in the dark.* Mark the positions of the north and south poles of the magnet on the paper, and place arrowheads here and there, indicating the direction in which the north pole of the needle points.

Lift the cardboard *vertically* from the magnet, and place it in a strong light (direct sunlight, if possible) for a few minutes.

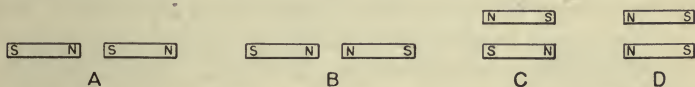


FIG. 89.

When the uncovered parts of the paper have turned dark, return the filings to the box and wash the paper immediately by moving it about in clean water, or letting water run over it from the faucet for a few minutes. Spread it out on a flat surface to dry, and when dry, fasten it in your note book. If left in the laboratory till the following day to dry, write your name on it for identification.

Experiment 112. — *To determine the shape and direction of the lines of force between and about two bar magnets in different relative positions.*

Experimental Work. — Proceed as above, either with or without blue-print paper, to study and make a record of the magnetic fields between and about two bar magnets in the different positions shown in Figure 89. For the positions shown in *A* and *B*, place the magnets about 4 cm. apart in the same groove of the board,

and determine the lines of force between and about their adjacent ends. For the arrangements shown in *C* and *D*, determine the lines of force between and all round the magnets. The last one or two cases may be omitted if one laboratory period does not give time enough for all of them. Mark the poles of the magnets in the figure or blue print, and place arrowheads on the lines, as in the preceding experiment.

Be careful to gather up all iron filings and return them to the sifter.

Discussion. — The following questions are to be answered from a study of the diagrams or blue prints you have made : —

1. Do the lines of force converge to a common point at or near the end of a magnet, or to different parts of a small area near the end?
2. Do any lines of force cross each other? What reasons have you for thinking that they can or cannot cross in any case?
3. Do lines of force extend between like poles or unlike poles, or both? What reasons have you for thinking that they can or cannot extend between like poles in any case?

XI. ELECTRICITY

EXERCISE 59. THE SIMPLE VOLTAIC CELL

References. — Adams, 456-463 ; Coleman, 441-447, 453 ; Car. & C., 428-431, 433-435 ; Ches. G. & T., 376-379 ; Hoad. Br., 346-350 ; Hoad. El., 387-391 ; Mumper, 251-253, 257 ; Jackson, 30-37, 51-52 ; Mil. & G., 351-352, 375-376 ; Went. & H., 271-274.

Apparatus. — Tumbler of dilute sulphuric acid (about 1 part by volume of concentrated acid to 20 parts of water) ; copper strip ; an amalgamated and an unamalgamated zinc plate, rod, or strip ; copper wire ; double connector (if necessary) ; magnetic needle (Fig. 87) ; glass tray or empty tumbler.

[The tumbler battery shown in Figure 90 is most convenient for this exercise ; but a wooden block with slots to support the plates will serve. The wires may be soldered or clamped to the plates ; but soldering will not hold in contact with an amalgamated surface of zinc. A photographer's developing tray of glass is very satisfactory for holding the plates when not in use. It should be large enough to hold the tumbler battery, also.]

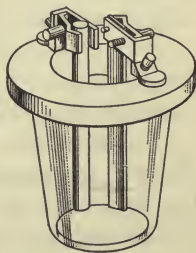


FIG. 90.

Experiment 113. — *To study the action of a simple voltaic cell ; and to test the presence of an electric current by its action on a magnetic needle.*

Experimental Work. — *a.* Keep the zinc and copper plates, when not in use, in the glass tray or empty tumbler provided for the purpose ; and keep the amalgamated zinc (the one of lighter

color) from contact with the other plates, to avoid any amalgamation of their surfaces. If the glass tray is large enough, stand the tumbler of acid on it. Avoid getting any of the acid on the table, the clothing, or the fingers.

Place the unamalgamated zinc plate (the darker one) in the tumbler of acid, and note the size and abundance of the bubbles that form on its surface. What becomes of them? They are bubbles of hydrogen (a constituent of the acid) which has been displaced by zinc, forming zinc sulphate. The zinc sulphate (a white solid) remains dissolved in the liquid, forming a colorless solution. Remove the zinc, and observe whether it has the appearance of having been partly consumed through previous use. Place it in the tray or empty tumbler.

b. Place the strip of copper in the acid, and observe whether any hydrogen bubbles form on its surface. Remove the copper, and observe whether it has been partly consumed through previous use.

When sulphuric acid acts on copper, copper sulphate is formed. This is a blue solid, which would remain dissolved in the liquid and would color it a greenish blue. Do you find the liquid thus colored? What conclusion do you draw from these observations?

c. Support the copper and the unamalgamated zinc plates in the acid by means of the clamps (or other device), and connect the copper wire with either of them, leaving its other end free. Do bubbles form at either or both plates? Press the free end of the wire against the other plate, and observe whether bubbles form at both plates. Remove the end of the wire, and observe. Repeat till sure of results. Avoid inhaling the unpleasant fumes from the battery.

The appearance of bubbles on the copper plate is not in itself evidence of chemical action on that plate. If there is such chemical action, the copper plate will be consumed after repeated use, as the zinc is, and the liquid will become greenish blue. Conclusion?

d. Connect the plates by means of the wire, using the clamps or double connector. (Do not twist wires together. Connections

must always be made to the bare wire; for the current will not pass through the insulation covering the wire.) Extend a portion of the wire parallel to the magnetic needle and several inches above it. Lower the wire without changing its direction (Fig. 91), and note the behavior of the needle as the wire approaches it. Note the effect of holding the wire under the needle. Disconnect the wire from one of the plates, and repeat. Result?

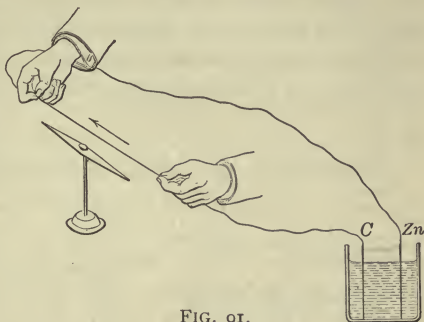


FIG. 91.

The deflection of the needle indicates the existence of a magnetic field about the wire, due to an electric current flowing through the wire from the copper to the zinc. (Since copper is not magnetic, it is evident that the wire is not magnetized.)

e. Connect the plates again, and estimate the relative amounts of hydrogen liberated at the two plates. The hydrogen liberated at the copper plate represents chemical action (of the acid on the zinc plate) which maintains the electric current in the wire. This is *useful* action, *i.e.* action by which an electric battery serves its intended purpose. The hydrogen liberated at the zinc plate represents *local action* (see text), which plays no part in maintaining the current in the wire, and hence results in wasted energy. Estimate the relative amounts of useful and wasteful action. Remove the zinc from the acid.

Experiment 114. — *To determine the effect of amalgamating the zinc.*

Experimental Work. — *a.* Place the amalgamated zinc and the copper plates in the acid. With the plates disconnected (circuit open), observe the size and abundance of the bubbles forming on

the zinc plate. Compare with the results obtained with the unamalgamated zinc in *a* above.

b. Connect the plates with the wire, and test the presence of an electric current, as in *d* above.

c. Estimate the relative amount of useful and wasteful action, as you did with the unamalgamated zinc in *e* above.

Place all the plates on the tray (or in the empty tumbler), being careful not to let the amalgamated zinc touch the other plates.

EXERCISE 60. THE MAGNETIC FIELD OF A CURRENT

References. — Adams, 472-473, 475 ; Coleman, 453-455 ; Car. & C., 433-434, 452-454 ; Ches. G. & T., 373 ; Hoad. Br., 371-373 ; Hoad. El., 408-409 ; Mumper, 257-258 ; Jackson, 119-124 ; Mil. & G., 355, 394-395 ; Went. & H., 278, 281.

Apparatus. — Small compass ; wire rectangle (Fig. 92) ; square of cardboard with slit from edge to hole at center ; electric cell ; tangent galvanometer or a flat, circular coil, with cardboard to fit, as in Figure 93 ; fine iron filings in sifter ; contact key (useful, but may be omitted).

[The wire rectangle should consist of 8 or 10 turns of No. 16, or 20 to 30 turns of No. 20 to 24 copper wire. The galvanometer should have 15 turns. A flat, circular coil of 15 to 20 turns and 12 to 15 cm. in diameter will serve instead. A good dry cell (as the Columbia), a Grenet, or a Fuller cell will furnish sufficient current. These cells all have a very low resistance, which is necessary.]

CAUTION. Throughout this exercise the circuit should be open when the current is not required, to avoid waste and to reduce polarization. If a Grenet cell is used, the circuit is closed by lowering the zinc into the liquid, and opened by raising it. *Keep the zinc raised when the current is not in immediate use.* If a dry cell is used and a contact key provided, always include the con-

tact key in the circuit. The circuit is opened and closed at the key. If a key is not provided, close the circuit by holding an end of the wire against a post of the cell. If the wire is not fastened, there will be less probability of keeping the circuit closed unnecessarily. A good dry cell furnishes a large current through circuits of low resistance, as in this exercise, if the service required is brief, with intervals of rest to permit recovery from polarization.

Experiment 115.—*To find the shape and direction of the lines of force about a straight conductor carrying a current, and the relation between their direction and the direction of the current.*

Experimental Work.—*a.* Support the cardboard in a horizontal position with one side of the wire rectangle passing through the hole at its center, and sprinkle iron filings on it. Connect the rectangle with the electric cell, including the contact key in the circuit, if one is provided.

The current leaves the cell from the carbon terminal and returns through the zinc terminal. Determine from this fact whether the current flows up or down on the side of the rectangle where the cardboard is placed. (The current flows in the same direction round the rectangle through all the turns composing it.)

With the circuit closed, tap the cardboard gently until the filings are arranged in distinct lines. Use the compass to determine the direction of the lines of force round the wire (*i.e.* the direction round the wire in which the *north pole* of the needle points). Break the circuit. Raise the zinc, if you are using a Grenet cell. Return the filings to the sifter.

Draw a figure in perspective, showing with arrowheads the direction of the current and the direction of the lines of force.

Several turns of wire are used in the rectangle merely to increase

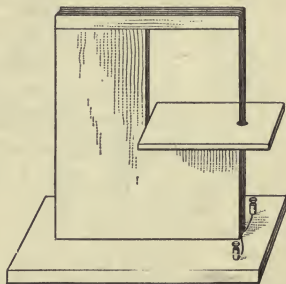


FIG. 92.

the effect of the current. The magnetic field is strengthened in proportion to the number of turns, but is otherwise the same as that about a single wire.

b. Grasp the wire above the cardboard with the right hand, with the thumb extended (up or down) in the direction in which the current was flowing. Do the fingers point round the wire in the direction of the lines of force (as the north pole of the compass needle points) or in the opposite direction? The relation between the direction of an electric current in a straight conductor and the direction of the lines of force round the conductor, when stated with reference to the thumb and fingers of the right hand, is known as the *right-hand rule*. State it in full.

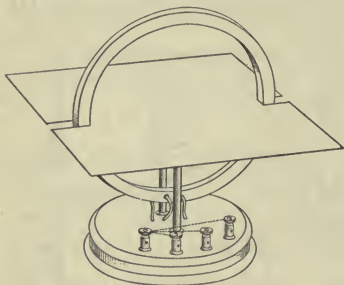


FIG. 93.

c. Close the circuit, and use the compass to determine the direction of the lines of force round the opposite side of the rectangle. Is their direction in agreement with the right-hand rule?

d. Observe the direction of the north pole of the needle with reference to the wire, when held just above the upper side

of the rectangle and when held just below it. Repeat with the rectangle standing in various directions, including east-west and north-south. Is the behavior of the needle in agreement with the rule?

Experiment 116.—*To study the magnetic field within and about a coil of wire carrying a current, with special reference to the relation between the direction of the current round the coil and the direction of the lines of force at its center.*

Experimental Work.—*a.* Connect the cell to the two binding posts of the galvanometer between which all the turns of the coil are included. Adjust the cardboard to the middle of the coil (Fig. 93), and close the circuit. Sprinkle filings on the card-

board, and tap with the finger. Determine with the compass the direction of the lines of force through the coil. Break the circuit.

If the direction in which the wire is wound round the coil from one post to the other is open to view, find from the connections with the cell in which direction the current was flowing round the coil. If the winding of the coil is not open to view, find the direction of the current round the coil from the right-hand rule and the known direction of the lines of force. (The rule applies to the parts of a curved conductor as well as to a straight one, as the change in the field caused by the bending of the conductor does not alter the relation expressed by the rule.) Draw a figure in perspective, showing the direction of the current and the direction of the lines of force within and about the coil. Return the filings to the sifter.

b. As applied to coils, a different statement of the right-hand rule is more convenient. Close the right hand and place it within the coil, with the extended thumb pointing in the direction of the lines of force *through the coil*. Do the fingers point in the direction of the current round the coil or in the opposite direction? State the rule in full.

EXERCISE 61. THE HELIX, THE ELECTRO-MAGNET, AND THE ELECTRIC BELL

References. — Adams, 478-483 ; Coleman, 456-458 ; Car. & C., 455, 457-458, 515 ; Ches. G. & T., 393, 442 ; Hoad. Br., 373-376, 418 ; Hoad. El., 410-414, 460 ; Mumper, 262, 266 ; Jackson, 124-129, 319 ; Mil. & G., 396-400 ; Went. & H., 282, 284-285.

Experiment 117. *To study the helix and the electro-magnet.*

Apparatus. — Soft iron rod of smaller diameter than a lead pencil ; 3 m. of small (No. 20 to 24) double-covered copper wire ; coarse iron turnings, tacks or small nails ; magnetic needle ; dry, Grenet, or Fuller cell.

Experimental Work.—*a.* Wrap half the wire round a lead pencil, forming a close coil of one or more layers and about 5 cm. long. Connect the wire with the cell, and find by means of the magnetic needle which end of the coil acts like the north pole of a magnet and which like the south pole. Break the circuit. Trace the direction of the current from the cell, and find which way it flowed round the coil. Grasp the coil in the right hand, with the fingers pointing round it in the direction of the current, and the thumb extended. Does the thumb point in the direction of the north pole or the south pole of the coil? State the relation in full.

Show that this relation amounts to the same thing as the one obtained with the flat coil in the preceding experiment.

b. Remove the helix from the pencil, and slip it over the iron rod, leaving about 2 cm. of an end of the rod exposed. With the circuit open, test the rod for magnetization by dipping an end of it into the iron turnings (or tacks). Close the circuit through the helix and repeat the test, noting carefully the quantity of turnings that cling to the rod. Observe the behavior of these turnings as you break the circuit. What does this behavior indicate? The helix and the rod together constitute an electro-magnet.

c. Wrap the remainder of the wire round the rod, leaving only a few inches at the ends for convenient connection with the cell. (If more convenient, replace the helix on the pencil to complete the winding.) Note the quantity of turnings that the electro-magnet will now pick up when the circuit is closed. How has the strength of the electro-magnet been affected by increasing the number of turns in the helix? Account for this effect.

d. With the circuit closed, test the polarity of the electro-magnet by means of the magnetic needle. Do like poles of the electro-magnet and the helix point in the same or in opposite directions? (If necessary, repeat the test of the helix alone.) Leave the cell disconnected.

Experiment 118. — *To study the construction and action of an electric bell.*

Apparatus. — An electric bell with a short piece of rubber tubing on the clapper to deaden the sound ; push button ; connecting wires ; dry, Leclanché, or Fuller cell.

Experimental Work. — *a.* Connect the cell with the bell, including the push button in the circuit. If the push button is not provided, close the circuit by touching an end of the wire to one of the poles of the cell. Ring the bell, and observe the sparks at the point where the spring that is attached to the clapper touches the point of a screw. The current crosses at this point ; hence the circuit is broken whenever the spring leaves the screw.

Trace the circuit through the bell from either binding post to the other. The metal frame of the bell commonly forms a part of the circuit. Does it in this bell ? There are four posts whose attachment to the base must be carefully examined. They are the two binding posts, the post that carries the screw that touches the spring, and the upright to which the clapper is attached. One or more of these will be found to be electrically insulated from the base by means of hard rubber washers. Such a post is not in metallic contact with the base, and the current cannot pass between them. The current is thus compelled to follow a definite course through the bell. Describe this course, referring to a simplified lettered diagram. Mark the insulated posts in this diagram, and represent by a dotted line the part of the circuit formed by the metal base of the bell.

What wires would you supply to complete the circuit if the base were of wood, and hence could not be utilized as a part of the circuit ?

b. Explain the action of the bell. How would the bell behave if the circuit were such as to send the current through the electro-magnet without crossing between the screw and the spring ?

c. Unscrew the cap of the push button, and observe its construction. Describe.

EXERCISE 62. THE ELECTRIC TELEGRAPH

References. — Adams, 484-486 ; Coleman, 459-463 ; Car. & C., 507-514 ; Ches. G. & T., 444-445 ; Hoad. Br., 419-427 ; Hoad. El., 461-468 ; Mumper, 264-265 ; Jackson, 290-299 ; Mil. & G., 401-403 ; Went. & H., 286.

Experiment 119. — *To set up a short distance telegraph line, and to study the construction and action of the instruments.*

Apparatus. — Two sounders ; two keys ; two gravity cells ; connecting wires.

Experimental Work. — *a.* Examine the sounder. Send the current from a gravity cell through it alone. The lever should be drawn down. Why? If it is not, the spring probably needs adjusting. Does the movement of the lever break the circuit, as it does in the electric bell?

b. Examine the key. Find the insulation that keeps the circuit open in the key when the switch is open and the lever up. Trace the circuit through the key (1) when the switch is open and the lever depressed ; (2) when the lever is up and the switch closed. Place the key in circuit with the sounder, and operate the sounder by means of it.

c. Connect up a telegraph line of two stations, having a sounder, a key, and a gravity cell at each station. The cells must be connected so as to act in the same direction round the circuit. Operate the line from each station in turn. Why is one key kept closed by means of the switch while the other key is in use?

Make a diagram of the circuit.

If gravity cells are used, leave them on closed circuit through the sounders when you have finished.

Experiment 120. — *To set up a long distance telegraph line ; and to study the construction and action of the relay.*

Apparatus. — Two sounders ; two keys ; two relays ; four to six gravity cells, as needed ; connecting wires.

Experimental Work. — *a.* Examine the relay. Find the posts by which the line circuit is connected with the electro-magnet. The local circuit, consisting of the sounder and the local battery, is connected with the other two posts. Trace the local circuit between these posts, and find where and how it is closed and opened by the movement of the vertical lever.

b. Connect the local circuit with the relay, using only one cell, if this is sufficient to operate the sounder. Operate the sounder by moving the lever of the relay back and forth by hand. How is this possible?

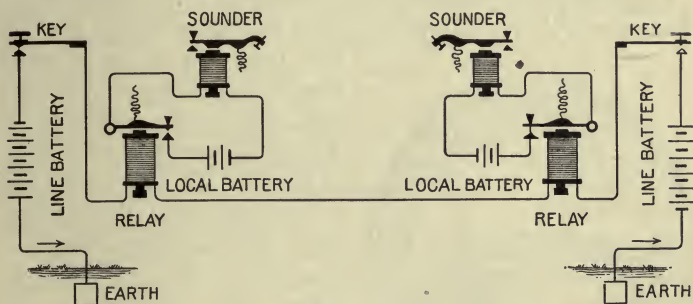


FIG. 94.

c. Connect up the local circuits at the two stations and the line circuit between them, as shown in Figure 94, using wire for the entire line circuit instead of the earth for the return. Open the switch at one station and operate it, at the same time observing the action of the relay and the sounder, another pupil also observing the action of the instruments at the other station. Now let the other pupil operate the key at his station, both observing as before.

Make a diagram of the entire telegraph system as you have arranged it.

If gravity cells are used, leave the switches closed when you have finished; if other cells are used, disconnect them or leave the switches open.

EXERCISE 63. THE TANGENT GALVANOMETER; POLARIZING AND NONPOLARIZING OR CONSTANT CELLS

References. — Adams, 465-470, 489; Coleman, 448-452, 464-467; Car. & C., 436-442, 464-466, 471-472; Ches. G. & T., 384-386, 400-402; Hoad. Br., 351-355, 382; Hoad. El., 392-398; Mumper, 254-256, 260, 282; Jackson, 40-50, 145; Mil. & G., 378-383; Went. & H., 275-276, 280.

Principle of the Tangent Galvanometer. — In the tangent galvanometer (Fig. 95) the current is sent through a vertical circular

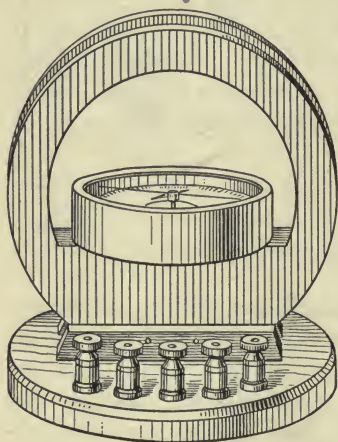


FIG. 95.

coil, consisting of one or more turns of insulated wire. A compass, with a scale graduated in degrees, is placed at the center of the coil. In Experiment 116 it was found that the lines of force due to a current in a circular coil are approximately straight near the center of the coil, and are at right angles to the plane of the coil. The magnetic field of the current is of sensibly uniform strength throughout this small space at the center; and, in a good instrument, the compass needle is short (not above 2 cm.) in

order that it may lie wholly in this uniform field, in whatever direction it may turn. The deflection of the needle is found by means of a long pointer, which is attached at right angles to the needle, and turns with it. All parts of the instrument except the needle must be nonmagnetic. The pointer is generally of aluminum, on account of its lightness.

In using a tangent galvanometer it must be placed with the plane of its coil in the magnetic meridian; in which position the lines of force of the coil at its center (where the needle is) are *at right angles* to the lines of force of the earth's field. When the galvanometer is in this adjustment and no current is flowing, the earth's field brings the needle to rest in the plane of the coil (along the line NS in Figure 96). When the current is flowing, its magnetic field tends to set the needle at right angles to this position. Thus two forces, acting at right angles to each other, are exerted on each pole of the needle, as shown in the figure; and the needle comes to rest in the direction of the resultant of these forces. The deflection of the needle caused by the current is the angle NOR .

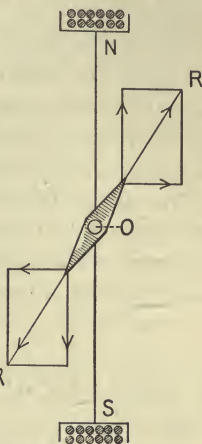


FIG. 96.

In Figure 97 ON represents the earth's magnetic force (acting on the north pole of the compass needle), and OB the magnetic force due to a current in the coil. The deflection in this case is NOA or a . Now, if the current is doubled, its magnetic force is doubled, as represented by OB' ; and the deflection becomes NOA' or a' . Similarly, if the current is increased to three times its first strength, its magnetic force is also trebled, as represented by OB'' , and the deflection becomes NOB'' or a'' . It is evident from the figure that the deflection increases less rapidly than the current ($a' < 2a$ and $a'' < 3a$): the current is not proportional to the deflection. But

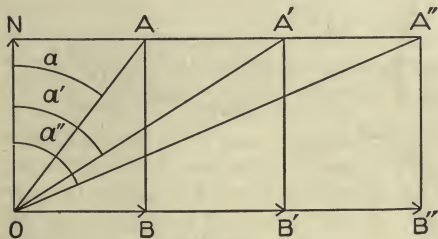


FIG. 97.

the current is increased to three times its first strength, its magnetic force is also trebled, as represented by OB'' , and the deflection becomes NOB'' or a'' . It is evident from the figure that the deflection increases less rapidly than the current ($a' < 2a$ and $a'' < 3a$): the current is not proportional to the deflection. But

the tangent¹ of angle a' is twice the tangent of angle a (i.e. $NA'/ON = 2 NA/ON$), and the tangent of a'' is three times the tangent of a (i.e. $NA''/ON = 3 NA/ON$). This relation is expressed in general terms as follows: *When currents of different strengths are sent through the same number of turns of the coil of a tangent galvanometer, the currents are proportional to the tangents of the angles of deflection which they produce.* This is why the instrument is called a tangent galvanometer.

To express this relation algebraically, let C and C' denote the strengths of two currents (measured in amperes), and let a and a' denote the deflections which they produce when sent through the same number of turns of a tangent galvanometer; then

$$C : C' :: \tan a : \tan a',$$

in which “ $\tan a$ ” is the usual abbreviation for “tangent of angle a .”

EXAMPLE. A current C causes a deflection of 50° , and another current C' causes a deflection of 25° . It is found from a table of tangents that $\tan 50^\circ = 1.19$ and $\tan 25^\circ = .466$.

Hence $C : C' :: 1.19 : .466$;
from which $C = 2.55 C'$.

¹ The ratio of one leg of a right triangle to the other is called the *tangent* of the angle opposite to the first leg. Thus the tangent of angle A (Fig. 98) is BC/AC or $B'C'/AC'$, BC and $B'C'$ being any line perpendicular to either side of the given angle. Since triangles ABC and $AB'C'$ are similar, the ratios BC/AC and $B'C'/AC'$ are equal. It is evident, therefore, that the tangent of an angle is a definite quantity, the value of which depends only upon the size of the angle. Angles are not proportional to their tangents, although small angles are very nearly so. The

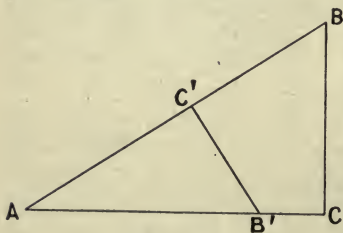


FIG. 98.

tangent of any angle from 0° to 90° may be found from a table of tangents (Appendix, Table XV).

A tangent galvanometer having a scale graduated in degrees may be thus used to determine the relative strengths of currents, but it does not give their numerical values. The numerical value (in amperes) may, however, be obtained by multiplying the tangent of the angle of deflection by a constant factor, found by experiment.

To adjust the Galvanometer.—The galvanometer is turned so that the two ends of the pointer stand at the two zero points of the circular scale. Since the two zero points are in a line perpendicular to the plane of the coil and the pointer is at right angles to the magnetic needle, this adjustment brings the plane of the coil into the magnetic meridian. This adjustment must not be disturbed during an experiment. All magnetic substances must be kept at a distance in adjusting and using the galvanometer.

To find the Deflection.—With most instruments it will be found that the two ends of the pointer do not stand exactly at the zero points at the same time, that the two ends of the pointer give slightly different readings for the same deflection, and that when the current is reversed in the coil, causing a deflection in the opposite direction, the two readings of this deflection differ not only from each other, but also from the first two readings. These discrepancies frequently amount to one or two degrees, and are due to various slight imperfections in the construction of the compass, and to an inexact adjustment of the instrument. To find the true value of the deflection due to a given current it is therefore necessary to read the position of both ends of the pointer, then to reverse the current and take two readings as before, and finally to take the average of these four readings as the true deflection.

Before taking a reading, the cover of the compass should be gently tapped with the finger to overcome friction, which might otherwise hold the needle in a wrong position.

A reading should be taken with one eye closed and the other held *vertically above* the pointer, otherwise the pointer will not appear in its true position over the scale. The eye is in the cor-

rect position when the faint image of it, formed by reflection from the glass cover of the compass, is directly under the pointer.

If the scale is graduated in single degrees, the reading should be estimated to tenths of a degree; if graduated in intervals of two degrees each, the reading should be taken to the nearest half degree.

Use of Different Numbers of Turns of the Coil. — The coil of a tangent galvanometer usually consists of fifteen turns, which are connected in groups of five to binding posts, so that the current can be sent through five, ten, or all fifteen turns, as desired. The number of turns used in any experiment should be the one giving deflections nearest to 45° , for the work is less accurate with either very large or very small deflections. A given error in reading the deflection involves the least error in the computed current when the deflections are between 30° and 60° .

It is important to understand why the deflection varies with the number of turns used. The tangent of the angle of deflection is proportional to the magnetic force of the current; and, with a current of given strength, this magnetic force is proportional to the number of turns through which the current flows.

Experiment 121. — *To determine the decrease of current strength due to polarization in different cells under the same conditions.*

Apparatus. — Tangent galvanometer; constant cell (gravity or Daniell); simple cell, as in Exercise 59; one or more cells for open circuit work (dry, Leclanché, Grenet, etc.); coil of wire having a resistance of about 3 ohms, with double connectors; connecting wires; watch or clock with second-hand.

[A tangent galvanometer to be satisfactory for students' use must conform to the following requirements: coil not less than 6 in. in diameter, having 10 or 15 turns in at least three combinations (usually 5, 10, and 15); short magnetic needle, with agate cap and light aluminum pointer; dial not less than 3 in. in diameter, and graduated in single degrees. Such an instrument will cost from \$6.00 to \$10.00.]

CAUTION. With considerable resistance in the circuit, the cur-

rent from a cell is small, and there is but little chemical action in the cell. Under such conditions polarization takes place slowly. When a cell is *short-circuited* (*i.e.* placed in a circuit having almost no resistance), the current is as large as the cell is capable of, and polarization takes place rapidly, if at all. When a simple cell is short-circuited, polarization is practically instantaneous. Hence in connecting up the different cells in the following experiment, care must be taken to include the resistance coil in the circuit before the circuit is closed. The experiment with the simple cell will fail completely if this precaution is not observed. The copper plate can be depolarized by heating it in a Bunsen flame. Wiping it with a cloth is not effective.

Experimental Work.—Adjust the galvanometer. Connect the simple cell with ten turns of the galvanometer coil, including the resistance coil (3 ohms) in the circuit. Read the deflection indicated by one end of the pointer as quickly as possible; and after one minute (by a clock or watch), read the deflection again, meanwhile observing the behavior of the needle. Remember always to tap the cover of the compass lightly with the finger before taking a reading. (In this exercise it is sufficiently accurate to take only one reading of a deflection, always reading the same end of the pointer, with the deflection in the same direction.)

Immediately after taking the second reading, bring the binding screws (double connectors) at the ends of the resistance coil together, and hold them in firm contact for one minute. This throws the resistance coil out of the circuit, and short-circuits the cell. Polarization, if not already completed before the short-circuiting, will now take place very rapidly (for reasons stated in the caution above). After one minute separate the binding screws, thus restoring the circuit as at first, and read the deflection. Record as indicated below. Remove the plates from the cell.

Repeat the above experiment with each of the cells provided, using in each case the number of turns of the galvanometer coil that will give a deflection between 30° and 60° , or as nearly

within these limits as possible. With a dry or a Grenet cell, try 5 turns first; with a Leclanché cell, 10 turns; with a gravity or a Daniell cell, 15 turns.

Data and Computations.—Record observations and computations as follows:—

CELL USED	SIMPLE	GRAVITY	DRY	ETC.
No. of turns of galvanometer coil used .	—	—	—	—
Deflection on closing circuit through resistance coil of 3 ohms	—	—	—	—
Deflection, same circuit, after it has been closed 1 min.	—	—	—	—
Deflection, same circuit, after cell has been on short circuit 1 min.	—	—	—	—
COMPUTATIONS				
Tangent of first deflection	—	—	—	—
Tangent of second deflection	—	—	—	—
Tangent of third deflection	—	—	—	—
Percentage of decrease of current in 1 min. through resistance coil	—	—	—	—
Percentage of decrease of current in 1 min. on short circuit	—	—	—	—

Discussion.—1. Name the cells used in the order of rapidity with which they polarize.

2. Account for the positions that the simple cell and the gravity (or Daniell) cell occupy in this list.

3. With which cells is the decrease of current greater on short circuit than with the resistance coil in the circuit? Why? With which cells (if any) is it less, and why?

4. What means are employed in the different cells to reduce or prevent polarization? (See text.)

EXERCISE 64. MEASUREMENT OF RESISTANCE BY SUBSTITUTION; THE LAWS OF RESISTANCE¹

References. — Adams, 492-495; Coleman, 468-471; Car. & C., 460-462, 464-466; Ches. G. & T., 406-407, 409-410; Hoad. Br., 377-380, 388; Hoad. El. 421-424; Mumper, 275-277; Jackson, 91-101, 160-161; Mil. & G., 363-365; Went. & H., 290, 294.

Method. — The resistance to be measured is connected in circuit with the galvanometer and a constant cell, and the deflection read as accurately as possible. The unknown resistance is then removed from the circuit, and a resistance box (Fig. 99) put in its place. Different resistances are introduced into the circuit through the box, by removing plugs, till the deflection of the galvanometer is the same as before. The

sum of the resistances of the box then included in the circuit is equal to the unknown resistance. For the equal deflections of the galvanometer indicate that the same

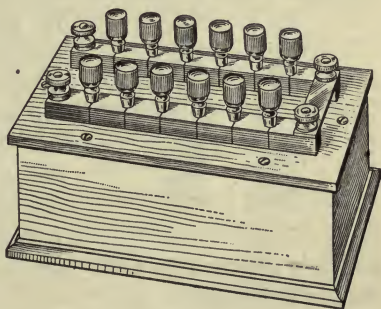


FIG. 99.

amount of current flows through the circuit in the two cases, and the cell has a constant E. M. F.; hence, according to Ohm's Law, the total resistance of the circuit must be the same in the two cases ($R = E/C$); hence, further, the resistance introduced from the box must be equal to the unknown resistance, no change having been made in the remainder of the circuit. The two deflections being equal and in the same direction, a single reading (of the same end of the pointer) for each deflection is sufficient.

¹ Either experiment of this exercise may be taken, and the other omitted.

Resistances obtained by this method may be in error by as much as 10%, even with careful work. This inaccuracy is due to the fact that, with a resistance of several ohms already in the circuit, a change of a few tenths of an ohm causes hardly a perceptible change in the deflection. For example, the deflection may be right, as nearly as it can be read, with a resistance of 3 ohms introduced in the box, while an additional resistance of .2 ohm causes no perceptible change. Consequently, the true value of the resistance may be 3 ohms, 3.2 ohms, or anything between, making a possible error of about 7%.

Use of the Resistance Box. — The resistance of the row of brass plugs and blocks on the resistance box is practically zero; but wherever a plug is removed, the resistance of the coil that bridges the gap (Fig. 100) is introduced in the circuit. The amount of this resistance is marked on the top of the box. When two or more plugs are removed, the resistance introduced is the sum of the resistances of the coils where the plugs are out.

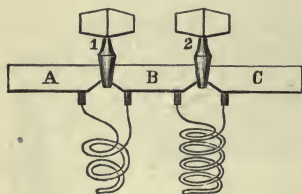


FIG. 100.

In finding the required resistance, the coils are tried in order from larger to smaller, as weights are tried in weighing.

Before using a resistance box, turn each plug in its hole, while exerting a moderate pressure. This insures good electrical connection between the plugs and the blocks, which is necessary, as the resistance at the points of contact between a loose plug and the adjacent blocks will make a set of measurements wholly unreliable.

A switch resistance box consists of three series of resistances, with a switch for each series. A resistance is introduced by turning a switch so as to rest upon the contact block beside which the desired number of ohms is marked. The total resistance introduced is the sum of the numbers at the three contact blocks with which the switches connect.

Experiment 122.—*To measure the resistance of a wire by the method of substitution.*

Apparatus.—A low resistance galvanometer; constant cell; resistance box; two coils of unknown resistance; connecting wires.

[Any low-resistance galvanometer that gives a suitable deflection may be used instead of a tangent instrument. An error of less than 15% or 20% is not to be expected, however, unless the dial is graduated in single degrees. With a gravity or a Daniell cell and a tangent galvanometer having a coil of 15 turns, the best results are obtained with resistance of 2 to 6 ohms.]

Experimental Work.—Adjust the galvanometer. Complete the circuit through the cell, the galvanometer, and one of the unknown resistances. Use the number of turns of the galvanometer coil which gives a deflection nearest to 45° . Read the deflection indicated by one end of the pointer, estimating tenths of a degree as accurately as possible. Substitute the resistance box for the unknown resistance, and adjust the resistance in it till the deflection (of the same end of the pointer in the same direction) is exactly the same as before. If the required resistance is uncertain by one or more tenths of an ohm, find and record the least and the greatest resistance in the box that give the correct deflection, and take their average as the value of the unknown resistance. If the deflection is seen to vary when no change has been made in the resistance of the circuit, the cell is at fault and dependable results are impossible. Record as indicated below.

Measure in the same way the other unknown resistance.

Find in the same way the resistance of the two wires when placed together in the circuit so that the whole current passes through one after the other. (This is called connecting in series.) The resistance of the two wires in series is the sum of their separate resistances. This will serve as a test of the accuracy of your results.

Data and Computations. —

	FIRST WIRE	SECOND WIRE	BOTH IN SERIES
Deflection	—	—	—
Least resistance in box giving an equal deflection	—	—	—
Greatest resistance in box giving an equal deflection	—	—	—
Average resistance in box giving an equal deflection (= resistance of wire)	—	—	—

Sum of the separate resistances of wires = ohms.
 Percentage of difference between sum of the separate
 resistances and resistance of both in series = %

Experiment 123. — *To study the relation between the resistance of a wire and its length and diameter, and to determine the relative resistance of German silver or other wire and copper wire of the same length and diameter.*

Apparatus. — Low-resistance galvanometer ; constant cell ; resistance box ; three pieces of wire of high specific resistance, of equal length, and two of them of the same diameter ; copper wire of same diameter as one of the others, and long enough to have a nearly equal resistance.

[Two pieces, 1 m. each, of No. 26 and 1 m. of No. 30, all of German silver, and 15 m. of insulated copper wire of either number are suitable. They may be in coils or stretched on a board. If stretched, the German silver wires may be bare or covered. See suggestions under Experiment 129 for making a piece of apparatus (Fig. 101) especially suited to both of these experiments.]

Experimental Work. — Following the directions of the preceding experiment, find the resistance (*a*) of one of the two larger high-resistance wires ; (*b*) of the two larger high-resistance wires

(of the same diameter), placed together in the circuit so that the whole current passes through one after the other; (*c*) of the smaller high-resistance wire; (*d*) of the copper wire. In each case find the least and the greatest resistance in the box that give the correct deflection, but record only their average.

Measure (unless given), and record the length and diameter of each wire.

If a gravity cell is provided for the work, leave it on a closed circuit through the resistance box, with the 20-ohm coil in the circuit. (The small current in such a circuit prevents the mixing of the two liquids by diffusion.)

Data. — Record as follows: —

	KIND OF WIRE	LENGTH OF WIRE	DIAMETER OF WIRE	DEFLECTION OF GALVANOMETER	RESISTANCE OF WIRE
<i>a</i>	—	—	—	—	—
<i>b</i>	—	—	—	—	—
<i>c</i>	—	—	—	—	—
<i>d</i>	—	—	—	—	—

Discussion. — 1. How nearly are the resistances found in *a* and *b* proportional to the lengths of the wires (considering the two wires in series in *b* as one wire)?

2. How nearly are the resistances found in *a* and *c* inversely proportional to the squares of the diameters of the wires?

3. Compute the ratio of the resistance of the high-resistance wire to the resistance of *an equal length* of the copper wire of the same diameter.

EXERCISE 65. THE RESISTANCE OF A CELL

Principle of the Method. — Let C (amperes) denote the current which an electro-motive force E (volts) maintains in a circuit whose total resistance is R (ohms), and C' denote the current

which *the same* electro-motive force maintains in a circuit whose resistance is R' ; then, by Ohm's Law,

$$E = CR = C'R',$$

from which we have the proportion,

$$C : C' :: R' : R. \quad (E \text{ constant.})$$

That is, the current due to a given E. M. F. is *inversely* proportional to the total resistance of the circuit (including the resistance of the battery).

In the following experiment a constant cell (E constant) is connected in circuit with a tangent galvanometer and a resistance box. Let r denote the resistance of the cell, g the resistance of the galvanometer coil, and R and R' resistances introduced in the box at different times. The resistance of the connecting wires is disregarded. The total resistance of the circuit will then be $r + g + R$ in the first case, and $r + g + R'$ in the second. Letting C and C' denote the currents maintained through these resistances respectively, the above proportion becomes

$$C : C' :: (r + g + R') : (r + g + R).$$

If a and a' denote the deflections caused by the currents C and C' respectively, then

$$C : C' :: \tan a : \tan a'. \quad (\text{Exercise 63.})$$

From these two proportions we have

$$(r + g + R') : (r + g + R) :: \tan a : \tan a'.$$

That is, with a constant E. M. F., the total resistance of the circuit is inversely proportional to the tangent of the angle of deflection.

Experiment 124. — *To find the resistance of a constant cell by the method of reduced deflection.*

Apparatus. — A tangent galvanometer of low resistance; constant cell (gravity or Daniell); resistance box; commutator (useful but not essential); connecting wires.

Experimental Work. — Adjust the galvanometer, and connect it in circuit with the cell and the resistance box. Include the commutator in the circuit, if one is provided. Connect with the number of turns of the galvanometer that gives a deflection nearest to 50° or 60° when no resistance is introduced in the box, and use only this connection throughout the experiment.

With no resistance introduced in the box ($R = 0$), read the position of both ends of the pointer as accurately as possible; reverse the current, and read again. The average of these four deflections is taken as the true deflection a .

Repeat with a resistance of 2 ohms in the box ($R' = 2$), and again with 4 ohms in the box ($R'' = 4$).

Record the resistance of the number of turns of the galvanometer used, as marked on the instrument or given by the teacher.

Data and Computations. —

Resistance, g , of the number of turns of the
galvanometer coil used = ohms.

Box RESISTANCE	DEFLECTION OF POINTER				AVERAGE DEFLECTION	TAN a
	E. end	W. end	E. end	W. end		
$R = 0$	— N.	— S.	— S.	— N.	$a =$ —	—
$R' = 2$	—	—	—	—	$a' =$ —	—
$R'' = 4$	—	—	—	—	$a'' =$ —	—

a. Compute the resistance r of the cell from the values of a , a' , R , and R' , substituting in the proportion

$$(r + g + R') : (r + g + R) :: \tan a : \tan a'.$$

b. Compute r from a , a'' , R , and R'' .

c. Compute r from a' , a'' , R' , and R'' .

d. With careful work these three independently determined values of r should differ by less than 6%. Find the percentage of difference between the greatest and the least of them.

EXERCISE 66. THE ELECTRO-MOTIVE FORCE OF CELLS¹

References. — Adams, 495 ; Coleman, 472-478 ; Car. & C., 465, 478 ; Ches. G. & T., 390-392, 404 ; Mumper, 278-279, 285 ; Jackson, 106-107, 182 ; Mil. & G., 359-362 ; Went. & H., 292, 296.

Experiment 125. — *To find the E. M. F. of cells with a tangent galvanometer having a high resistance.*

Apparatus. — A tangent galvanometer of high resistance ; gravity or Daniell cell ; one or more cells for the measurement of their E. M. F. ; commutator (useful but not essential).

[The galvanometer must have a resistance of at least 100 ohms ; 200 ohms or more is better. The E. M. F. of the gravity or Daniell cell should be found with a voltmeter from day to day, and marked on the cell.]

The Principle of the Method. — The fall of potential in the different parts of a circuit (including the liquid of the cell) is everywhere proportional to the resistance of the different parts. For example, if the resistance of the cell is 1 ohm and that of the external circuit 99 ohms, the fall of potential in the liquid of the cell from the zinc to the carbon plate is 1 % of the E. M. F. of the cell, and the fall of potential in the external circuit is 99 % of it. There is, therefore, an error of 1 % in assuming that the fall of potential in the external circuit is equal to the E. M. F. of the cell. But if the resistance of the external circuit is 999 ohms, the error in this assumption is only .1 %.

It will be seen from the above that, if the coil of a tangent galvanometer has a resistance of at least two or three hundred ohms, the potential difference between its terminals when connected with a cell will be sensibly equal to the E. M. F. of the cell, and the tangents of the angles of deflection will be proportional to this

¹ It is intended that only one of the experiments of this exercise be taken, the choice depending upon the laboratory equipment.

E. M. F. If a denotes the deflection when the galvanometer is connected with a cell whose E. M. F. is E , and a' the deflection when it is connected with a cell whose E. M. F. is E' , then¹

$$E : E' :: \tan a : \tan a'. \quad (\text{Resistance constant.})$$

Experimental Work.—Adjust the galvanometer, and connect with the gravity or the Daniell cell. Read both ends of the pointer, reverse the current, and read again. Record the E. M. F. of the cell, as marked on it by the instructor.

Connect each of the cells in turn with the galvanometer, and read the deflections as before.

Data and Computations.—Compute the E. M. F. of each cell from the formula

$$E : E' :: \tan a : \tan a',$$

in which E and a refer to the gravity or the Daniell cell, and E' and a' to each of the other cells in turn. Record as follows:—

KIND OF CELL	DEFLECTION		AV. DEFLECTION a	TAN a	E. M. F.
	E. end	W. end			
Gravity	— N.	— S.	—	—	— (given)
	— S.	— N.			
Leclanché	— N.	— S.	—	—	—
	— S.	— N.			
Etc.	—	—	—	—	—
	—	—			

¹ This relation does not hold with a low-resistance galvanometer, for in that case the resistance of the cells would be a large part of the whole resistance of the circuit, and the currents (and the tangents of the angles of deflection) would be as largely affected by the unequal resistances of the cells as by their unequal electro-motive forces.

Experiment 126. — *To find the E. M. F. of cells by the method of equal deflections.*

Apparatus. — A high-resistance galvanometer (not necessarily a tangent instrument) with its resistance marked on it ; resistance box ; gravity or Daniell cell, with its E. M. F. marked on it ; one or more cells for the measurement of their E. M. F.

[Any simple galvanoscope will serve, provided it has a sufficient number of turns to give a suitable deflection in a circuit with one cell and a total resistance of 200 ohms or more.]

Principle of the Method. — Let E denote the E. M. F. that maintains a current C in a circuit whose total resistance is R , and E' the E. M. F. that maintains an *equal* current through a total resistance R' ; then, by Ohm's Law,

$$C = \frac{E}{R} = \frac{E'}{R'} ;$$

from which

$$E : E' :: R : R'. \quad (\text{Current constant.})$$

That is, the E. M. F. necessary to maintain a given current is proportional to the total resistance of the circuit.

Experimental Work. — Adjust the galvanometer and connect it in circuit with the gravity or Daniell cell and the resistance box ; but before closing the circuit introduce a high resistance in the box, to avoid possible damage to the galvanometer by too large a current. Adjust the resistance in the box so as to make the deflection between 40° and 50° , and read one end of the pointer as accurately as possible. Record the deflection, the resistance R introduced in the box, and the resistance g of the galvanometer coil. If $R + g$ is greater than 100 ohms, the resistance of the cell may be disregarded ; but its approximate value, if known, may be added as a part of the resistance of the circuit.

Substitute each of the cells in turn for the one just used, and repeat the above work, in each case adjusting the resistance R in the box so that the deflection of the same end of the pointer in the same direction is exactly equal to the first deflection.

Data and Computations. — Let E denote the known E. M. F. of the gravity cell and R the box resistance used with it, E' the E. M. F. of any one of the other cells, and R' the box resistance used with it. The currents were equal (how do we know?); hence, disregarding the resistances of the cells,

$$E : E' :: R + g : R' + g. \quad (\text{Why?})$$

From this proportion compute the E. M. F. of each of the cells used. Record as follows:—

Deflection for each adjustment = °
Resistance of galvanometer coil g = ohms.

KIND OF CELL	BOX RESISTANCE R	$R + g$	E. M. F.
Gravity	— ohms	— ohms	— volts (given)
Etc.	—	—	—
	—	—	—

Experiment 127. — *To find the E. M. F. of cells by the method of reduced deflection.*

Apparatus. — Galvanometer; resistance box; gravity or Daniell cell with its E. M. F. marked on it; one or more cells for the measurement of their E. M. F.

[Almost any galvanometer will serve, of either low or high resistance. A tangent galvanometer with a 15-turn coil is as good as any. A very sensitive galvanometer, as an astatic or a D'Arsonval, requires the use of a shunt or of very high resistances.]

Principle of the Method. — Let C denote the current that an E. M. F. E maintains through a total resistance R , and C_1 the current when the resistance is increased by R_1 ; *i.e.*

$$C = \frac{E}{R} \text{ and } C_1 = \frac{E}{(R + R_1)}.$$

Let R' denote the total resistance through which an E. M. F. E' maintains the first current C , and R_1' the added resistance necessary to reduce the current to C_1 ; *i.e.*

$$C = \frac{E'}{R'} \text{ and } C_1 = \frac{E'}{(R' + R_1')}.$$

Hence
$$C = \frac{E}{R} = \frac{E'}{R'}, \quad (1)$$

and
$$C_1 = \frac{E}{(R + R_1)} = \frac{E'}{(R' + R_1')}. \quad (2)$$

From (1)
$$\frac{R}{E} = \frac{R'}{E'}. \quad (3)$$

From (2)
$$\frac{(R + R_1)}{E} = \frac{(R' + R_1')}{E'}. \quad (4)$$

Subtracting the members of (3) from the corresponding members of (4) we have

$$\frac{R_1}{E} = \frac{R_1'}{E'},$$

or

$$E : E' :: R_1 : R_1'.$$

That is, the two electro-motive forces are proportional to the *added* resistances which reduce the equal currents equally.

Experimental Work.—Adjust the galvanometer, and connect all the turns of its coil in circuit with the gravity or Daniell cell and the resistance box. If necessary, introduce resistance in the box to reduce the deflection to about 50° . Read one end of the pointer as accurately as possible. Record the deflection and the box resistance. Increase the box resistance till the deflection is reduced nearly one half. Record the exact deflection and the box resistance.

Substitute each of the cells in turn for the one just used; and in each case adjust the box resistance so as to give first and second deflections (of the same end of the pointer in the same direction) exactly equal to the two deflections in the first case. Record the box resistances.

Data and Computations. — Compute the E. M. F. of each cell from the proportion

$$E : E' :: R_1 : R_1',$$

in which E denotes the E. M. F. of the gravity cell and E' the E. M. F. of any other cell used, R_1 the *added* resistance causing the reduced deflection with the gravity cell, and R_1' the added resistance with the other cell. The resistances of the galvanometer and of the different cells are not required. Record as follows : —

First deflection (for all cells) = °
 Second deflection (for all cells) = °

KIND OF CELL	BOX RESISTANCE		ADDED RESISTANCE, R_1	E. M. F.
	1st	2d		
Gravity	— ohms	— ohms	— ohms	— volts (given)
Etc.	—	—	—	—
	—	—	—	—

EXERCISE 67. THE ELECTRO-MOTIVE FORCE AND RESISTANCE OF A CELL

References. — Adams, 495-496 ; Coleman, 472-478 ; Car. & C., 465, 474, 478 ; Ches. G. & T., 390-392, 403-404 ; Hoad. Br., 386, 390, 393-394 ; Hoad. El., 430, 436 ; Mumper, 273, 278-279, 285 ; Jackson, 171, 175, 182 ; Mil. & G., 358-362, 369-370 ; Went. & H., 292, 296.

Experiment 128. — *To find the E. M. F. and the resistance of a cell by means of a voltmeter and an ammeter.*

Apparatus. — Voltmeter ; ammeter ; cells of different kinds ; short connecting wires.

Experimental Work. — Find the E. M. F. of a cell by connecting its poles directly to the voltmeter ; then connect the cell with the ammeter, to determine the current that the cell gives when short-circuited (the resistance of the ammeter being negligible). Repeat with each of the cells provided, always connecting with the voltmeter first, as most of the cells will begin rapidly to polarize when connected with the ammeter, thus diminishing their E. M. F.

Data and Computations. — When a cell is connected with the ammeter, the external resistance may be disregarded, with very little error ; *i.e.* the resistance of the cell may be taken as the whole resistance of the circuit. Upon this assumption, the resistance of the cell is found by dividing the E. M. F. of the cell by the reading of the ammeter ($R = E / C$). Record as follows :—

KIND OF CELL	E. M. F. OF CELL	CURRENT THROUGH AMMETER	RESISTANCE OF CELL, $R = E / C$.
	— volts	— amperes	— ohms
	—	—	—
	—	—	—

EXERCISE 68. FALL OF POTENTIAL ALONG A CONDUCTOR

References. — Adams, 497 ; Coleman, 475-478 ; Car. & C., 478 ; Ches. G. & T., 390-392, 404 ; Hoad. Br., 386, 394 ; Hoad. El., 430, 433 ; Mumper, 285 ; Jackson, 106-107, 171, 175, 182 ; Mil. & G., 359-362 ; Went. & H., 292, 296.

Experiment 129. — *To study the relation between the fall of potential in the different parts of a circuit and the resistances of those parts.*

Apparatus. — Tangent galvanometer of high resistance, or voltmeter ; board with stretched wires ; one or more cells, as needed ; connecting wires.

[The directions for the experiment are adapted to the tangent galvanometer. A voltmeter simplifies the work, but the smallest divisions of the scale must not be greater than .1 volt. A d'Arsonval galvanometer may be used, if provided with a suitable shunt to reduce the deflections. Three German silver wires, — two of No. 26 and one of No. 30, — each stretched between binding posts 1 m. apart, and 15 m. of No. 30 insulated copper wire, also connected with a pair of binding posts (Fig. 101), are

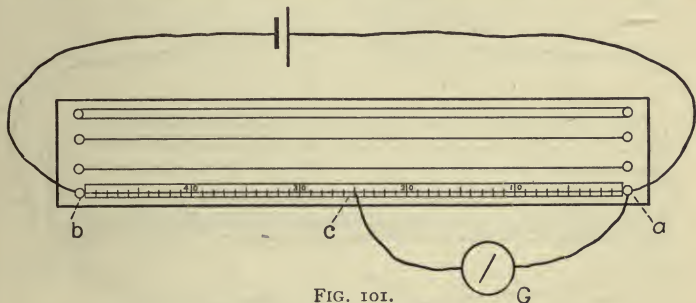


FIG. 101.

suitable for this experiment and also for Experiment 123. The No. 30 German silver wire must be bare, and should be stretched over a meter stick, for convenience in measuring off lengths. The distances between the binding posts can be reduced to 50 cm. by using wire having a specific resistance of 40 to 50 instead of German silver ; and with such wire somewhat larger sizes can be used, giving greater durability. It is only necessary that the resistances of the wires be large enough to give good results (2 to 5 ohms each), and that the copper wire be of the same diameter as one of the others.]

Experimental Work. — *a.* Connect the cell (or two or more cells in series) with the binding posts *a* and *b* (Fig. 101), between which the smaller high-resistance wire is stretched. Connect one

terminal of the high-resistance coil of the galvanometer (or the voltmeter) with the post *a*. Connect a short wire with the other terminal of the galvanometer, and press the other end of this wire firmly down upon the stretched wire exactly 25 cm. from *a*. Read the deflection indicated by both ends of the pointer. Repeat, taking the point of contact *c* 50 cm., 75 cm., and 100 cm. from *a*. (If the length of the wire is 50 cm., reduce each of these distances one half.)

Reverse the connections with the galvanometer, so that the deflections will be in the opposite direction, and repeat the readings for each of the above adjustments. The average of the four

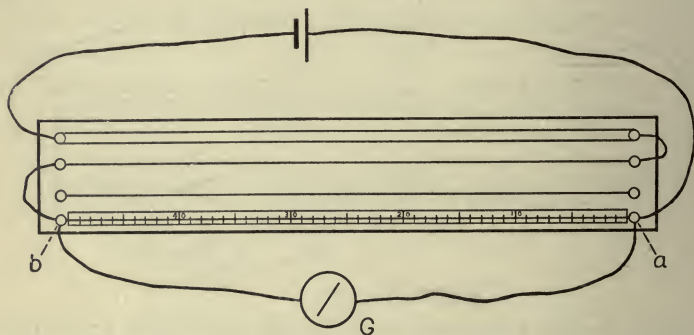


FIG. 102.

readings for each adjustment is taken as the true deflection. If a voltmeter is used, a single reading for each adjustment is all that is required.

b. Connect the battery in series with the stretched copper wire, one of the larger high-resistance wires, and the smaller high-resistance wire, as shown in Figure 102, using short connecting wires between the posts. Find the deflection of the galvanometer when connected with the binding posts at the ends of the smaller high-resistance wire (see figure). Reverse the current through the galvanometer, and take the average of the four readings as the true deflection.

In the same way find the deflection of the galvanometer when connected with the ends of the larger high-resistance wire (making no change in the main circuit), and when connected with the ends of the copper wire.

Record the lengths and diameters of the different wires.

Data and Computations. — Let l denote the length of stretched wire between the terminals of the galvanometer in Part a of the experiment. Record as follows:—

PART a

l	DEFLECTION		AV. DEFLECTION a	TAN a	$l \div \text{TAN } a$
	E. end	W. end			
25 cm.	— N.	— S.	—	—	—
	— S.	— N.			
50 cm.	— N.	— S.	—	—	—
	— S.	— N.			
75 cm.	— N.	— S.	—	—	—
	— S.	— N.			
100 cm.	— N.	— S.	—	—	—
	— S.	— N.			

PART b

STRETCHED WIRE BETWEEN GALVANOMETER TERMINALS			DEFLECTION		AV. DEFLECTION a	TAN a
Kind	Length	Diameter	E. end	W. end		
Copper	— cm.	— cm.	— N.	— S.	—	—
			— S.	— N.		
			— N.	— S.		
			— S.	— N.		
			— N.	— S.		
			— S.	— N.		

Discussion.—1. The resistance of any portion of the stretched wire is proportional to its length; the fall of potential in any portion is proportional to its resistance (Ohm's Law as applied to the parts of a circuit); and the potential difference between the terminals of the galvanometer (*i.e.* the fall of potential in the part of the stretched wire between these terminals) is proportional to the tangent of the angle of deflection (why?); hence the lengths of the parts of the stretched wire between the terminals of the galvanometer in Part *a* should be proportional to the tangents of the angles of deflection (*i.e.* the quotient $l \div \tan \alpha$ should be constant). Within what percentage of difference do you find this relation to hold?

2. Do the deflections of the galvanometer indicate equal or unequal fall of potential in the whole length of the smaller high-resistance wire in Parts *a* and *b*? How do you account for this?

3. From the measured diameters of the two high-resistance wires, compute the ratio of the resistances of 1 m. of each. Compute the ratio of the fall of potential in one to the fall of potential in the other in Part *b* (given by the ratio of the tangents of the deflections). How should these ratios compare, and why? Is the fall of potential more or less rapid in the larger wire than in the smaller? Why?

4. Assuming Ohm's Law, find, from the data obtained in Part *b* with the copper wire and the high-resistance wire of the same diameter, the ratio of the resistance of the latter to the resistance of an *equal* length of the copper wire. This ratio is the specific resistance of the high-resistance wire referred to copper.

EXERCISE 69. MEASUREMENT OF RESISTANCE WITH THE WHEATSTONE BRIDGE

References: The Wheatstone Bridge

Adams, 498; Car. & C., 476-479; Ches. G. & T., 412; Hoad. Br., 389; Hoad. El., 434; Mumper, 284-286; Jackson, 106, 162-168; Went. & H., 291-293.

The d'Arsonval Galvanometer

Adams, 490 ; Coleman, 484 ; Car. & C., 473 ; Ches. G. & T., 405 ; Hoad. Br., 385 ; Hoad. El., 429 ; Mumper, 261 ; Jackson, 151-152 ; Mil. & G., 356 ; Went. & H., 280.

The Astatic Galvanometer

Coleman, 483 ; Hoad. Br., 383 ; Hoad. El., 427 ; Jackson, 149 ; Went. & H., 280.

Principle of the Bridge. — When two points, *A* and *B* (Fig. 103), on an electric circuit are connected by two branches, as *AMB* and *ANB*, the fall of potential is the same in both branches, since in both it is the potential difference between the points *A* and *B*. Let *N* be the point in one branch whose potential is the same as that of a given point *M* in the other branch. Then the fall of

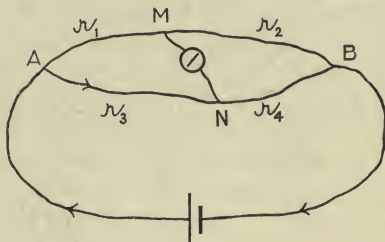


FIG. 103.

potential in *AM* is equal to that in *AN*, and the fall in *MB* is equal to that in *NB*. But, by Ohm's Law, the fall of potential in *AM* is to that in *MB* as the resistance of *AM*, or r_1 , is to the resistance of *MB*, or r_2 ; and similarly in the other branch. Hence $r_1 : r_2 :: r_3 : r_4$. If any three of these resistances are known, the fourth can be computed from this proportion.

The equipotential points *M* and *N* are found experimentally by means of a sensitive galvanometer placed in the "bridge" joining the two branches. The resistances are varied (as described below) till the deflection of the galvanometer is zero. We then know that there is no current through the wire joining *M* and *N*, and consequently that these points are at equal potentials. The two branches of the divided battery circuit *AMB* and *ANB*, together

with the cross branch MN , constitute a *Wheatstone bridge*. The parts AM , MB , AN , and NB are the four *arms* of the bridge. The Wheatstone bridge is made in various forms, but the above statement of the principle holds for all.

The Slide Wire Bridge.— This form of the Wheatstone bridge (Figs. 104 and 105) derives its name from a stretched bare wire,



FIG. 104.

the parts of which, l_1 and l_2 , constitute two arms of the bridge. The resistance to be measured (r_1 in the figure) is placed in either of the arms AM or MB , and a resistance box is placed in the other. The resistance of the large brass connecting bars in these arms is, of course, negligible. The battery terminals are

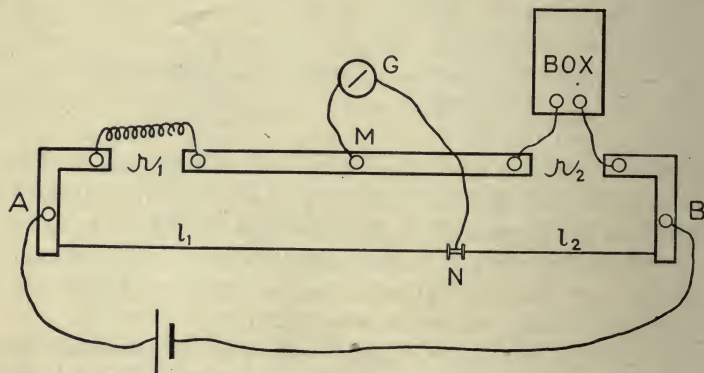


FIG. 105.

connected to posts at A and B . One terminal of the galvanometer is connected with a post at M , and the other is brought in contact with any desired point of the stretched wire by means of the sliding contact key N .

When the position of the key N is such that there is no deflection of the galvanometer on closing the circuit through it, the resistances of the segments l_1 and l_2 into which the wire is divided by the point of contact of the key are in the same ratio as r_1 and r_2 ; or, since the lengths l_1 and l_2 are in the same ratio as their resistances, $l_1 : l_2 :: r_1 : r_2$. Hence if r_1 is the unknown resistance, it is computed from the equation $r_1 = l_1 r_2 / l_2$.

The lengths l_1 and l_2 can be more accurately determined when neither is small; it is therefore best to have them nearly equal. This requires that the box resistance be nearly equal to the resistance to be measured. Hence in measuring a resistance, begin by introducing in the box a resistance estimated to be somewhere nearly equal to it. With the battery circuit closed, touch the slide wire with the contact key near one end, and note the direction of the deflection. Slide the key to about an equal distance from the other end, and repeat. (*Do not slide the key when closed: the wire would be damaged by scraping it.*) If the deflection is in the same direction as before, the resistance in the box is much too large or too small. If you are doubtful which is the case, make contact nearer either or both ends, till an opposite deflection is obtained. Having properly adjusted the box resistance, and having found two points between which the correct point of adjustment lies (the two points giving deflections in opposite directions), the adjustment is completed by noting the decreasing deflection of the galvanometer in either direction as the points of contact are taken at diminishing distances on each side of the point sought. With a sensitive d'Arsonval galvanometer, the adjustment should be right within 1 mm.

The Resistance-coil Bridge. — In each of the arms AM and AN of this form of bridge a resistance coil (1, 10, or 100 ohms) is introduced by removing a plug, as in a resistance box. The resistance of the brass connecting bars is negligible. The resistance to be measured (r_2 in the figure) is placed in either of the arms MB or NB , and a resistance box r_4 (in the figure) is placed

in the other. The box resistance is adjusted to give a zero deflection of the galvanometer.

The results are most accurate when the coil used for r_1 is the one most nearly equal to r_2 and when the ratio r_1/r_3 is so taken that r_4 is not far from the full capacity of the box. It is generally better to begin with equal values for r_1 and r_3 , and to change the ratio later if this is found to be desirable. The circuit through the galvanometer is momentarily closed, by means of the contact key,

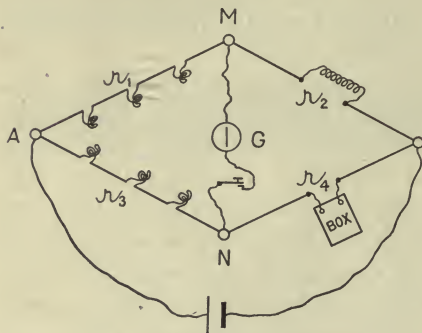


FIG. 106.

ment of the resistance. The battery circuit may be kept closed; but if a key is provided for this circuit, it is closed before and opened after the galvanometer circuit.

In measuring a resistance, note first the direction of the deflection when the box resistance is zero; then introduce a resistance estimated to be about equal to the one you are measuring. If the deflection is in the same direction as before, introduce more resistance; if it is in the opposite direction, replace the plug firmly and introduce a smaller resistance. Proceed thus down to the smallest resistance in the box, or until there is no deflection. When the correct adjustment is secured, r_3 is found from the equation $r_2 = r_1 r_4 / r_3$.

Experiment 130. — *To measure electrical resistance by means of a Wheatstone bridge.*

Apparatus. — A Wheatstone bridge; d'Arsonval or astatic galvanometer; dry (or other) cell; resistance box; resistance to be measured; connecting wires.

[The slide wire bridge is recommended unless the laboratory is already supplied with the other form. A satisfactory d'Arsonval galvanometer, similar to Figure 107, very sensitive, suitable for use with the bridge and for experiments on induced currents, can be bought for \$7.00 to \$12.00. These are dead-beat instruments, which is a very important advantage over the astatic type.]

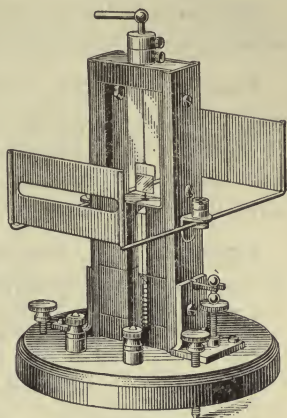


FIG. 107.

Experimental Work. — In measuring any resistance with a Wheatstone bridge, follow the directions given above. Find the resistance of such of the following conductors as are provided: —

1. The filaments of incandescent lamps; *e.g.* a 16-candle, 110-volt lamp; a 32-candle, 110-volt lamp; a 16-candle, 220-volt lamp; a 32-candle, 220-volt lamp.
2. Coils of electro-magnets; *e.g.* of a telegraph sounder, telegraph relay, electric bell, and the armature of a motor or dynamo.
3. The coil of a galvanometer or a voltmeter.

Experiment 131. — *To measure the resistance of a cell.*

Apparatus. — As for Experiment 130; also two of the cells whose resistance is to be found.

Experimental Work. — The two cells whose resistance is to be determined must be of the same kind and, as nearly as possible, in the same condition, in order that their electro-motive forces may be equal. Place them, connected in series and *opposing each other*, in one arm of the bridge. When thus connected their combined E. M. F. is zero, and their effect in the bridge is that of a simple resistance equal to the sum of their separate resistances. A third cell must, of course, be used in the usual manner to supply a current to the bridge.

Experiment 132.—*To find the relative resistance of different metals, referred to copper.*

Apparatus.—As for Experiment 130; also copper and other wires of the same diameter and any convenient lengths.

Experimental Work.—Find and record the length, diameter, and resistance of each wire. Compute the ratio of the resistance of each wire to the resistance of a copper wire of the same length and diameter. Compare the values obtained with the values given in tables. Enter data and computations in tabular form.

Experiment 133.—*To study the relation between the resistance of a wire and its cross section.*

Apparatus.—As for Experiment 130; also two or more wires of the same material and length, but of different diameters; micrometer screw (unless the diameters of the wires are given).

Experimental Work.—Find the lengths, diameters, and resistances of the different wires. Find within what percentage of error the measured resistances and diameters agree with the known law. Enter data and computations in tabular form.

EXERCISE 70. ARRANGEMENT OF CELLS

References.—Adams, 499–504; Coleman, 477, 479–482; Car. & C., 467–470; Ches. G. & T., 396–399; Hoad. Br., 358–362; Hoad. El., 401–405; Mumper, 283; Jackson, 38; Mil. & G., 384–386; Went. & H., 297.

Experiment 134.—*To study the arrangement of cells in series and in parallel; and to find which arrangement gives the larger current through a given external resistance.*

Apparatus.—Tangent galvanometer of low resistance and one of high resistance (the latter can be dispensed with), or a voltmeter and an ammeter; two cells of the same kind; resistance box; double connectors; connecting wires.

[The cells should be of the same size and as nearly as possible

in the same condition, in order that they may have equal E. M. F. and approximately equal resistance. The resistance of good dry cells is so small that they fail to show the advantage of connection in parallel, unless the whole external resistance is only a few hundredths of an ohm).

Experimental Work. — Find the ratio of the E. M. F. of a battery of two like cells in series (Fig. 108) to that of one cell, and the ratio of the E. M. F. of the two cells in parallel (Fig. 109) to that of one cell. If a tangent galvanometer of high resistance is provided for this purpose, follow the method of Experiment 125 and the form of record given below ; with a high-resistance galvanometer, which is not a tangent instrument, follow the method of Experiment 126 ; with a low-resistance galvanometer, follow the method of Experiment 127 ; with a voltmeter, measure directly the E. M. F. of each cell separately, of both in series, and of both in parallel, as in Experiment 128.

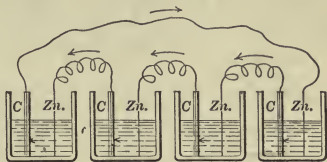


FIG. 108.

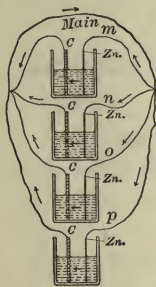


FIG. 109.

Connect the low-resistance galvanometer (or the ammeter) in circuit with the resistance box and one cell. Use the number of turns of the coil which gives a deflection nearest to 45° with no box resistance ; and use the same connection in all that follows. Read to the nearest degree the deflection (of one end of the pointer in one direction) with a box resistance R of 0 ohms ; with $R = 3$ ohms ; and with $R = 20$ ohms. Repeat with a battery of two cells in series and the same box resistances. Read the same end of the pointer as before, with the deflection in the same direction. Repeat with a battery of two cells in parallel and the same box resistances. Record as indicated below. If an ammeter is used, all the readings will be in amperes.

in all that follows. Read to the nearest degree the deflection (of one end of the pointer in one direction) with a box resistance R of 0 ohms ; with $R = 3$ ohms ; and with $R = 20$ ohms. Repeat with a battery of two cells in series and the same box resistances. Read the same end of the pointer as before, with the deflection in the same direction. Repeat with a battery of two cells in parallel and the same box resistances. Record as indicated below. If an ammeter is used, all the readings will be in amperes.

Data and Computations. — Make diagrams of the series and parallel arrangements, representing the resistance box and the galvanometer in the circuit. With a tangent galvanometer of high resistance and a low-resistance instrument (tangent or other), record as follows : —

E. M. F. OF TWO CELLS IN SERIES AND IN PARALLEL COMPARED WITH THAT OF A SINGLE CELL. (HIGH-RESISTANCE GALVANOMETER.)

NO. AND ARRANGEMENT OF CELLS	DEFLECTION		AV. DEFLECTION	TANGENT	RATIO OF ELECTRO-MOTIVE FORCES
	E. end	W. end			
1	— N.	— S.	—	$\tan a$	
	— S.	— N.			
2, in series	— N.	— S.	—	$\tan a'$	$\tan a' \div \tan a$
	— S.	— N.			
2, in parallel	— N.	— S.	—	$\tan a''$	$\tan a'' \div \tan a$
	— S.	— N.			

CURRENT FROM TWO CELLS IN SERIES AND IN PARALLEL COMPARED WITH THAT FROM SINGLE CELL. (LOW-RESISTANCE GALVANOMETER.)

NO. AND ARRANGEMENT OF CELLS	DEFLECTION WITH BOX RESISTANCE R			ARRANGEMENT GIVING THE LARGER CURRENT
	$R = 0$ ohms	$R = 3$ ohms	$R = 20$ ohms	
1	—	—	—	—
2, in series	—	—	—	—
2, in parallel	—	—	—	—

Discussion. — 1. How does the E. M. F. of the two cells in series compare with that of one cell? the E. M. F. of the two cells in parallel?

2. From the known law of resistances in series and in parallel (which holds for cells as well as for other conductors), how does the resistance of a battery of two like cells in series compare with that of one cell? the resistance of a battery of two like cells in parallel?

3. Letting E denote the E. M. F. and r the resistance of one cell, R the external resistance, and C the current, write the formula for the current from a battery of two cells in series; also the formula for the current from a battery of two like cells in parallel.

4. Show from the results of the experiment which arrangement of cells gives the larger current through a very low external resistance ($R=0$); and which arrangement gives the larger current through a considerable external resistance ($R=20$).

5. Account for these results by means of the formulas given in answer to the third question.

EXERCISE 71. MEASUREMENT OF ELECTRICAL POWER

References. — Adams, 541–544; Coleman, 486–491; Ches. G. & T., 387; Hoad. Br., 395; Hoad. El., 437; Mumper, 280–281; Jackson, 110, 112–113, 331; Mil. & G., 404–407; Went. & H., 299–302.

Electrical Power. — The unit of electrical power is the energy expended per second by a current of 1 ampere in any part of the circuit in which the fall of potential is 1 volt. This unit is called the *watt*. The power of an electric current, or the total energy expended by it in the entire circuit in one second, measured in watts, is equal to the product of the E. M. F. and the current; *i.e.* $P = EC$ watts, in which P denotes the electrical power, E the E. M. F. in volts, and C the current in amperes.

The power used in any part of a circuit is measured in watts by the product of the current and the fall of potential in that

part of the circuit. For example, if a 16-candle lamp takes a current of .5 ampere and the potential difference between its terminals is 110 volts, the power expended in it is $.5 \times 110$, or 55 watts. This is 3.44 watts per candle power ($55 \div 16 = 3.44$).

Experiment 135.—*To measure the power generated by a battery when lighting an incandescent lamp; and to determine the percentage of the total power consumed in the battery and in the lamp.*

Apparatus.—A small incandescent lamp; a sufficient number of cells to light the lamp; voltmeter; ammeter; two double connectors; connecting wires.

[Dry cells are best and most convenient. Lamps requiring from two to four dry cells in series are suitable. If the laboratory is not provided with such lamps, the coil of an electro-magnet or any resistance coil may be used instead.]

Experimental Work.—Connect the lamp and the ammeter in circuit with one cell. If the current is not sufficient to light the lamp, add a second cell in series with the first, and, if necessary,

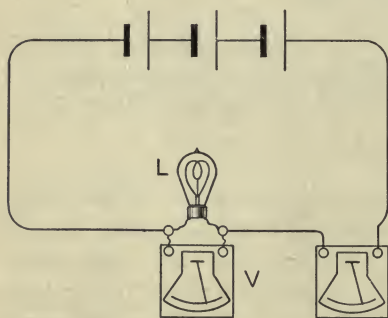


FIG. 110.

a third and a fourth cell. Use only a sufficient number of cells to light the lamp brightly; if too many are used, the filament will be burned out and the lamp destroyed.

Connect the voltmeter as a shunt to the lamp (V , Fig. 110) to determine the potential difference between its terminals.

Read the ammeter and the voltmeter. Do not keep the circuit closed longer than is necessary. Make a diagram of the circuit.

Find the E.M.F. of the battery by connecting its terminals

directly to the voltmeter (the lamp and the ammeter being removed from the circuit).

Record the candle power of the lamp.

Data and Computations. — Let P_l denote the fall of potential in the lamp and P_b the fall or loss of potential in the battery, when on the lamp circuit. (The loss of potential in the battery is practically zero when connected directly with the voltmeter, as explained in Experiment 125.) Hence, letting E denote the E. M. F. of the battery, and assuming the loss of potential in the ammeter and the connecting wires to be negligible, $E = P_b + P_l$ (*i.e.* the total fall of potential in the whole circuit is equal to the E. M. F. of the battery).

If the current through the lamp circuit is denoted by C , the total power generated by the battery when on the lamp circuit is EC watts, the power expended in the lamp is $P_l C$, and the power lost in the battery, due to internal resistance, is $P_b C$.

Record data as follows, and perform the indicated computations :—

Current supplied to the lamp C	=	amperes.
Potential difference between the lamp terminals P_l	=	volts.
E. M. F. of battery E	=	volts.
Candle power of the lamp	=	
Loss of potential in the battery when on the lamp circuit $P_b = E - P_l$	=	volts.
Total power generated by the battery when on the lamp circuit EC	=	watts.
Power expended in the lamp $P_l C$	=	watts.
Power lost in the battery $P_b C$	=	watts.
Percentage of total power utilized in the lamp	=	%
Percentage of total power lost in the battery	=	%

Discussion. — 1. By Ohm's Law, the losses of potential in the battery and in the lamp are proportional to their respective resistances, and the total resistance is E/C . From this compute the

resistance of the battery and the resistance of the lamp. (Since P_b , as found, really includes the loss of potential in the ammeter and the connecting wires, the computed battery resistance will include the resistance of the ammeter and the connecting wires.)

2. Compute the watts per candle power consumed by the lamp.

EXERCISE 72. INDUCED CURRENTS

References. — Adams, 505-512, 524 ; Coleman, 492-495 ; Car. & C., 480-482 ; Ches. G. & T., 415-422 ; Hoad. Br., 397 ; Hoad. El., 439-440 ; Mumper, 287-291 ; Jackson, 132-137 ; Mil. & G., 412-417 ; Went. & H., 313-315.

Apparatus. — A d'Arsonval or astatic galvanometer ; induction coil with movable primary and iron core ; dry cell ; bar magnet ; connecting wires.

[The usual form of separable induction coil, in which the secondary coil consists of many turns of fine wire, requires a d'Arsonval or an astatic galvanometer of fairly high resistance. With an astatic galvanometer of low resistance, the secondary coil should consist of a few turns of large wire, like the primary.]

Experiment 136. — *To study the laws of current induction by magnets.*

Experimental Work. — *a.* Since the galvanometer is to be used to determine the direction as well as the existence of induced currents, it is first necessary to observe the direction of the deflection due to a current whose direction is known. Use the cell for this purpose ; but before closing the circuit, connect the terminals of the galvanometer with a short wire, which will act as a shunt to the galvanometer, permitting only a small fraction of the current to pass through it. (This is a necessary precaution with a sensitive instrument.) Observe the direction of the deflection, and note (from the battery connections) by which terminal the

current enters the galvanometer. A current entering by the other terminal would cause a deflection in the opposite direction. Hence in the following experiments the direction of the deflection will indicate by which terminal the current enters the galvanometer; and from this the direction of the current can be traced through the entire circuit.

b. Connect the galvanometer with the larger coil of wire (called the secondary coil), placed at a distance of a meter or more. The circuit consists only of the coil, the galvanometer, and the connecting wires.

Thrust the north pole of the magnet suddenly into the coil, while observing the galvanometer. Note the direction of the deflection. Observe the effect of removing the magnet. Repeat till you are sure of the results. (The galvanometer must be far enough away not to be directly affected by the motion of the magnet. Test this by inserting and withdrawing the magnet with the circuit broken.) From the direction of the deflection, determine the direction of the current round the coil (clockwise or counter clockwise as you look down upon it), when the north pole of the magnet is inserted and when it is removed. Applying the right-hand rule, determine whether the current induced in the coil makes its upper end N or S when the north pole of the magnet is inserted and when it is removed.

Draw diagrams similar to Figure III, showing the polarity of the magnet and the direction in which it is moving, and the resulting polarity of the coil and direction of the current round it.

c. Is there a current when the magnet is at rest within the coil? What is the experimental evidence?

d. Study the effect of inserting and removing the south pole of the magnet. Answer all the questions of (*b*) for this case, and draw diagrams as before.

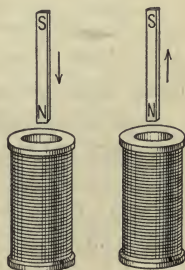


FIG. III.

Experiment 137.—*To study the laws of current induction by currents.*

Experimental Work.—*a.* Connect the cell with the smaller coil (called the primary) so as to make the lower end of the coil a north pole. The galvanometer is to be connected with the secondary coil as before.

Determine, from the deflection of the needle, the direction of the current in the secondary coil when the north pole of the primary coil is inserted into and when it is removed from the secondary coil. Make diagrams similar to Figure 112, showing the

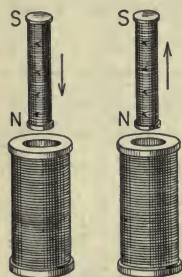


FIG. 112.

direction of the current in the secondary coil in each case and the resulting polarity of this coil.

b. With the primary coil at rest in the secondary, study the currents induced when the circuit is closed through the primary, and when it is broken. (Make and break the circuit by touching the connecting wire to one of the binding posts, and removing it.)

Compare the directions of the induced currents with the directions of the currents induced when the primary coil was inserted and removed.

c. Repeat the work of (*b*) with the iron core within the primary coil. Note whether the deflections are greater or less than before. State and account for the effect of the core.

d. With the primary circuit closed, insert and remove the primary coil and the iron core together, first quickly, then more and more slowly, and note the effect of the rate of motion on the amount of the deflection. What law of electro-magnetic induction is illustrated?

Discussion.—The induced current in the secondary coil is called *direct* if its direction round the coil is such that like poles of the secondary coil and the magnet or the primary coil point in the same direction; *inverse*, if their like poles point in opposite

directions. Thus a direct induced current flows in the same direction round the coil as the inducing current in the primary coil, and an inverse induced current flows in the opposite direction. State the different ways in which you obtained —

1. An inverse induced current.
2. A direct induced current.
3. Does the magnetic field due to the induced current aid or oppose the insertion and removal of the magnet or the primary coil? (Consult the text and reference books for a discussion of the connection of this fact with the principle of the conservation of energy.)
4. In which cases in these experiments was the induced current due to an increase in the strength of the magnetic field within the secondary coil? Was the induced current in these cases direct or inverse?
5. In which cases was the induced current due to a decrease in the strength of the magnetic field within the secondary coil? Was the induced current in these cases direct or inverse?
6. What law of electro-magnetic induction is illustrated by the effect of the iron core?

EXERCISE 73. THE ELECTRIC MOTOR AND DYNAMO

References. — Adams, 513-523; Coleman, 500-505; Car. & C., 493-500; Ches. G. & T., 428-436, 439-441; Hoad. Br., 406-415, 439; Hoad. El., 445-459; Mumper, 292-295; Jackson, 195-215; Mil. & G., 416-427; Went. & H., 314-325.

Experiment 138. — *To study the construction and action of a small motor.*

Apparatus. — Small motor (Fig. 113); dry cell; compass; small square of cardboard; iron filings in sifter; screw-driver; connecting wires. [The cheapest grade of motor is not recommended. One costing \$2.00 to \$3.00 gives much better service.]

Experimental Work. — *a.* Trace the circuit from one binding post of the motor to and from the armature, and through the

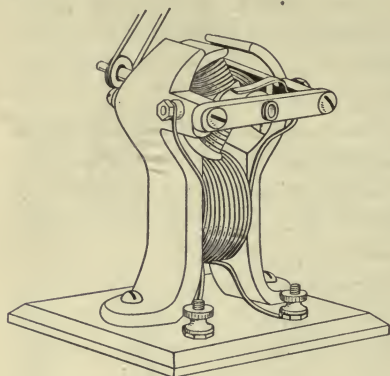


FIG. 113.

coil of the field magnet to the other post. (The circuit through the armature will be studied later.) If the armature and the coil of the field magnet are connected in series, the motor is said to be *series-wound*; if they are connected in parallel, it is *shunt-wound*. Is this motor shunt or series wound?

b. Connect the motor with the dry cell, and note

by which post the current enters it. Determine the polarity of the field magnet from the known direction in which the current flows round its coil (applying the right-hand rule), and test your conclusion by means of the compass.

Note the brush (upper or lower) by which the current enters the armature, and the direction in which the armature rotates.

c. Interchange the battery connections with the binding posts of the motor. Does this reverse the direction of the current in the coil of the field magnet? Is the polarity of the field magnet reversed? (Test with the compass.) Does the current enter the armature by the same brush as before or by the other one? Does the armature rotate in the same direction as before?

d. Unscrew the horizontal bar that supports the armature on the side opposite the commutator brushes. (The upper side of this bar should be distinguished by a file mark, to assist in replacing it with the same side up. There are commonly slight inequalities in the bar which throw the armature slightly out of position and hinder or even prevent its rotation, if the bar is

reversed when it is replaced.) Remove the armature and inspect the winding of its coils and their connection with the segments of the commutator. Pass a current through the armature by holding the ends of the connecting wires from the cell against any two segments of the commutator; and, while doing so, test the polarity of each pole of the armature by means of the compass. Draw a diagram of the armature, indicating the segment of the commutator by which the current enters and the one by which it leaves the armature, the direction of the current in each coil, and the polarity of the different poles.

e. Test the polarity of the poles of the armature when the connecting wires are pressed with thumb and finger against opposite sides of the commutator and the armature is turned into different positions, bringing different pairs of the commutator segments into contact with the connecting wires. Continue this study until you have determined at what two points in a complete rotation the current is reversed in any one coil (the wires being held opposite to each other in fixed positions, like the brushes of the motor).

f. Send the current from the cell through the coil of the field magnet, turn the magnet into a horizontal position with the brushes underneath, place the cardboard over the magnet, and study the magnetic field in the space where the armature belongs, by means of iron filings sprinkled on the cardboard. (If the motor is series-wound, the circuit through the field magnet will be broken by the removal of the armature. It can be closed by bringing the brushes into contact with each other.) Make a diagram of the poles of the magnet and the lines of force between them. Test the strength of the magnet after breaking the circuit, by observing its effect on the iron filings and the compass. This *residual magnetism*, as it is called, is important in most forms of dynamos, but is of no value in motors.

g. Replace the armature in position, and test it by finding whether it will run as before. Trace the direction of the current (with the circuit open) from either post to the other, round the

coil of the field magnet and all the coils of the armature; and determine by the right-hand rule the resulting polarity of the field magnet and the polarity of any coil of the armature in the different parts of a complete rotation. If this is correctly done, it will be seen that the commutator reverses the current in each

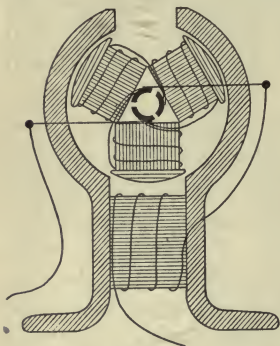


FIG. 114.

coil of the armature as it passes two fixed positions in each rotation, and that this keeps the armature in continuous rotation by the attraction of unlike poles and the repulsion of like poles of armature and field magnet.

Make a section diagram of the motor, similar to Figure 114, and in it indicate the direction of the current in the coils of the field magnet and the armature, the polarity of the field magnet and the poles of the armature, and the direction of rotation.

h. Account for the direction of rotation (the same or opposite) when the direction of the current through the motor is reversed.

Experiment 139. — *To study the action of the motor when run as a dynamo.*

Apparatus. — The same as for the preceding experiment, together with a low-resistance galvanometer or galvanoscope and a piece of stout cord four or five feet long.

Experimental Work. — *a.* Connect the motor with the galvanometer, using all the turns of the coil. Pass an end of the cord half round the pulley attached to the axle of the armature; and, while another pupil holds the motor on the table, set the armature in rapid rotation by drawing the cord quickly from end to end over the pulley. This should generate sufficient current to deflect the galvanometer.

Note the direction of the deflection when the armature is rotated in the same direction as that in which it turns as a motor, and also when rotated in the opposite direction. From the direction of the deflection in each case, determine the direction of the current through the galvanometer (making a test of the galvanometer by means of the cell, if necessary), and from this the direction of the current through the armature.

b. The current generated by the rotation of the armature in this experiment is too weak either to materially strengthen or weaken the residual magnetism of the field magnet. The polarity of this residual magnetism is determined by the direction of the much stronger current last sent through the coil from the cell. Find this polarity by means of the compass, and indicate it in a diagram like that of the motor in the preceding experiment.

In running the machine effectively as a dynamo, the direction of the current generated must be such as to strengthen the existing polarity of the field magnet. In which direction (the same as that in which it turns as a motor or the opposite) must the armature be turned to accomplish this result? When the rotation is in this direction, does the current flow through the armature in the same direction as when it is running as a motor, or in the opposite direction? (The answers to these questions are not the same for shunt-wound as for series-wound machines. Remember that the current enters the armature by the positive brush when the machine is run as a motor, and leaves by the positive brush when it is run as a dynamo.)

c. Represent the above facts in the diagram of the dynamo. State the points of resemblance and the points of difference between the diagrams of the motor and the dynamo.

Discussion (Oral).—1. Does the current generated in a dynamo help or hinder the rotation of its armature? Answer from the facts of the experiment, as shown in your diagrams.

2. Show that the laws of electro-magnetic induction apply in the generation of a current by a dynamo.

EXERCISE 74. THE GILLEY GRAMME RING DYNAMO AND MOTOR

References. — The same as for Exercise 72.

Experiment 140. — *To study the construction and action of a model Gramme ring dynamo and motor.*

Apparatus. — Gilley's model Gramme ring and motor (Fig. 115); two dry cells; cardboard; iron filings in sifter; compass; connecting wires.

[The Gilley model Gramme ring and motor is manufactured by the L. E. Knott Apparatus Co., Boston. It is a very instructive piece of apparatus, especially designed for laboratory work. The following directions are adapted from Mr. Gilley's exercises on the machine.]

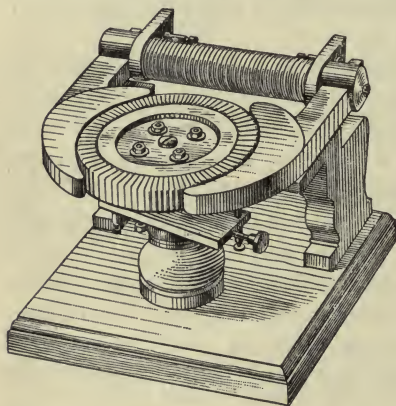


FIG. 115.

Experimental Work. —

The Field Magnet. a. Lift the armature off and set it aside. Send the current from one cell through the coil of the field magnet. Lay the cardboard over it, and study the

magnetic field by means of iron filings and the compass. Make a diagram of the field magnet, showing the direction of the current round the coil, the north and south poles of the magnet, and the lines of force between the poles.

b. Note the behavior of the compass needle and the iron filings when the circuit is closed, and when it is open. The stronger the magnetic force, the more rapidly will the compass needle vibrate

when disturbed. The magnetism remaining in the electro-magnet when there is no current through its coil is called *residual magnetism*. What do you infer concerning the relative amount of the residual magnetism?

c. Reverse the current through the coil, and note the effect on the polarity of the field magnet. Result?

The Armature. — *d.* Remove the field magnet and replace the armature. Send the current from one cell through the armature by connecting the cell with the binding posts on the brush holder. Observe that there is a continuous coil, wound throughout in the same direction round the iron ring of the armature, and that this coil is connected at four equidistant points with the corresponding sections of the commutator on the under side. The current divides in passing through the armature from one brush to the other, part going through one half of the coil and part through the other half. The current flows in opposite directions round these two parts of the coil. (Why?) A Gramme ring armature is, therefore, a double electro-magnet, with like poles of the two semicircular magnets together.

Place the cardboard over the armature, and study its magnetic field by means of the iron filings and the compass. The double north and south poles of the armature are where the lines of force extend radially (*i.e.* where the compass points exactly toward the center of the armature). Make a diagram of the armature, representing its north and south poles, the lines of force, and the direction of the current round the halves of the coil.

The Commutator. — *e.* With the current flowing through the armature and the cardboard removed, hold the compass close beside the armature at one of its poles; and, keeping it in this position, note the behavior of the needle as you slowly turn the armature. Stop the armature at the instant when the needle suddenly changes its direction, and observe whether this is a position in which the brushes change contact from one section of the commutator to the next.

Again turn the armature slowly, moving the compass at the

same time, so as to keep it exactly at one of the poles. Stop the armature at the instant when the needle indicates a sudden change in the position of the pole, and find the point to which the pole has shifted. Find what change of contact between the commutator and brushes caused the shifting of the pole. Does the other pole shift at the same time so as to remain opposite to the first?

f. How many times during a complete rotation do the poles shift to a new position? Why?

Through what angle do the poles turn with the armature before shifting to a new position? Through what angle do they shift? Do they shift in the direction of rotation or in the opposite direction?

What is the greatest angle that the straight line through the poles of the armature makes in either direction with the line through the points of contact of the brushes with the commutator?

g. How would these results differ if the commutator had eight sections? sixteen sections? (The commutators of dynamos and motors for practical use have many sections.)

h. Find the north and south poles of the armature; then, without changing its position, turn the brush holder through 180° . What is the effect on the position of the north and south poles? Explain.

The Complete Motor, Series-wound. — *i.* Place the armature and the field magnet in position. Connect the two cells in series, and join one pole of the battery to a binding post of the field magnet, and the other pole to one of the binding posts on the brush holder. Connect the other binding posts of the field magnet and brush holder by a short wire. The motor is now *series-wound*. Turn the brush holder till the points of contact of the brushes are in a line parallel to the two arms of the field magnet. The armature should rotate.

Make a diagram of the motor, showing the connections, the direction of the current round the coil of the field magnet and the two branches of the armature coil, the polarity of the field magnet and the armature, and the direction of rotation. If you

have difficulty in determining the polarity of the armature either by the right-hand rule or the compass, test it with the compass after removing the coil of the field magnet from the circuit.

Referring to your diagram, show whether all the attractions and repulsions between the poles of the field magnet and the poles of the armature are such as to cause rotation in the observed direction.

j. With the connections the same as before, turn the brush holder through 180° . Account for the reversal of the rotation.

k. Turn the brush holder back through 90° , bringing the points of contact of the brushes into a line at right angles to the arms of the field magnet. Why does the armature not rotate?

The Complete Motor, Shunt-wound.—*l.* Connect the battery wires to the binding posts of the field-magnet coil, and connect the armature as a shunt to this coil. The motor is now *shunt-wound*. The position of the brush holder is the same as with series winding. Make a diagram showing connections, direction of rotation, etc., as before.

m. Is the rotation reversed on turning the brush holder through 180° ? Give reason.

n. Is the rotation reversed on interchanging the battery connections? Explain.

Experiment 141.—*To study the action of the model Gramme ring machine when run as a dynamo.*

Apparatus.—The same as for the preceding experiment, together with a low-resistance galvanometer.

Experimental Work.—*a.* Restore the connections and the adjustment of the brush holder exactly as shown in your diagram under (*l*) in the preceding experiment. See that the direction of rotation is the same as before, and note by which binding post the current *enters* the armature. (This is the positive armature post.)

Disconnect the armature from the battery circuit, leaving the

field magnet in the circuit as it was; and connect the armature with the galvanometer, using all its turns. Rotate the armature as rapidly as possible, by a sudden push of the finger, in the direction in which it previously turned as a motor, and note the direction of the galvanometer deflection. From the direction of the deflection, find the direction of the current in the armature circuit (testing the galvanometer with a cell, if necessary), and note the post by which the current *leaves* the armature. This is the positive post, since the E. M. F. is generated in the armature coil and the rise of potential must therefore be in it.

Does the current flow in the same direction in the armature as it did when the machine was running as a motor, or in the opposite direction? Draw a diagram as for the motor, representing the direction of the current in the coils of the field magnet and armature, the polarity of the field magnet, and the polarity of the armature resulting from the current generated by its rotation.

b. Find in the same way the direction of the current generated by rotating the armature in the opposite direction, all the other conditions remaining the same as before.

Leave the cells disconnected.

Discussion. — 1. Is the polarity of the armature such as to aid or oppose its rotation when it is run as a dynamo? Show that the answer is in agreement with the principle of the conservation of energy, and that if the opposite were true, it would be an exception to this principle.

2. From a comparison of your diagrams, show whether (the connections remaining the same) the armature of a shunt-wound dynamo must be turned in the direction in which it would run as a motor, or in the opposite direction, if it supplies the current for its own field magnet. (The direction of the current that a dynamo sends through its field magnet must be such as to strengthen the existing polarity of the residual magnetism. Why?)

3. What is the advantage of a large number of segments in the commutator of a motor?

EXERCISE 75. THE TELEPHONE

References. — Adams, 530-532 ; Coleman, 508-510 ; Car. & C., 520-523 ; Ches. G. & T., 446 ; Hoad. Br., 429-431 ; Hoad. El., 469-471 ; Mumper, 299 ; Jackson, 308-316 ; Mil. & G., 441-443 ; Went. & H., 332.

Experiment 142. — *To study the construction and action of a telephone receiver.*

Apparatus. — A d'Arsonval or astatic galvanometer of high resistance ; telephone receiver.

Experimental Work. — *a.* Unscrew and remove the cap that covers the disk of the receiver. Remove the disk. Describe the parts exposed to view. Is the disk attracted by the magnet? Of what material is it? Make a section diagram of the receiver.

b. Connect the receiver with the galvanometer. Note the behavior of the galvanometer when you touch the magnet with the disk, and again when you remove the disk. Do the deflections indicate currents in the same or in opposite directions in the two cases? Account for these currents.

c. Place the disk in position on the receiver, and observe whether the galvanometer indicates a current when you press the disk lightly at its center with the finger, so as to bring it nearer the magnet, and again when you remove the pressure.

If you should speak into the receiver when it is on a closed circuit, what currents would be generated, and why? Why would such currents not cause a deflection of the galvanometer?

Experiment 143. — *To study the action of a telephone line consisting of two receivers.*

Apparatus. — Two telephone receivers at opposite ends of the laboratory or in adjacent rooms, connected with long wires ; tuning fork ; rubber mallet.

[The circuit may be permanently set up between two binding

posts at each end of the line, so that it is only necessary for the pupil to connect the receivers with the binding posts.]

Experimental Work.—*a.* Listen at one receiver while your companion touches the stem of a vibrating fork to the disk of the receiver at the other end of the line.

b. Try speaking to one another, using the receivers alternately as receiver and transmitter.

Explain the action of such a telephone line.

Experiment 144.—*To study the construction and action of a microphone.*

Apparatus.—Telephone receiver; dry cell; two battery or electric light carbons; microphone; tuning fork and rubber mallet; watch.

Experimental Work.—*a.* Connect the pieces of carbon, the receiver, and the battery as shown in Figure 116, so that the circuit

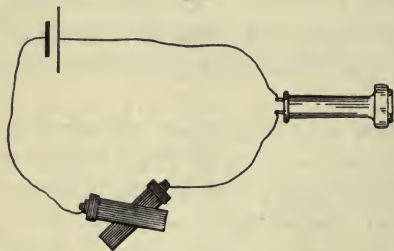


FIG. 116.

will be closed by touching the carbons together. Place the receiver to the ear, and touch one carbon to the other, varying the pressure, or rub one carbon lightly over the other. The receiver should give out a loud, rattling sound. The resistance at the points of

contact of the carbons with each other varies with the pressure. How does this account for the sounds from the receiver?

b. If the microphone is without an induction coil, connect it in series with the receiver in the battery circuit (Fig. 117); if it has an induction coil, connect the cell with the primary coil and the telephone receiver with the secondary. (The microphone is permanently connected in series with the primary coil.)

Hold the receiver to the ear, and tap lightly on the base of the

microphone, or rub the finger lightly over it. Listen to a watch lying on the microphone. Touch a *faintly* sounding tuning fork to the microphone.

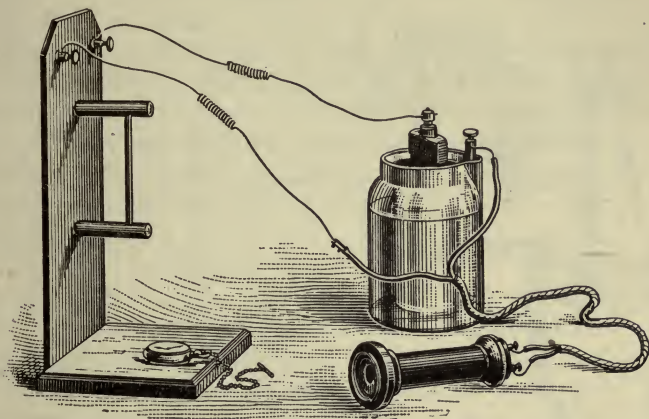


FIG. 117.

How does the microphone reproduce these different sounds? Is the reproduction like the original sound in character? Is it louder?

Experiment 145. — *To study the construction and action of a complete telephone line.*

Apparatus. — A telephone line consisting of two telephones made for laboratory use.

[A battery call telephone (Fig. 118), costing from \$5 to \$7 each, is suitable for this experiment.]

Experimental Work. — The principles of the modern telephone are covered by the preceding experiments; the details of construction differ in different telephones. The following general directions indicate the principal matters of detail to be made out in the study of the laboratory telephone.

a. Trace out the connections by which the bell is included in the line circuit when the receiver is on the hook.

b. Trace the line circuit through the telephone when the button is pushed to ring the bell of the other telephone. Is the bell of one telephone rung by the battery of the other, or by its own?

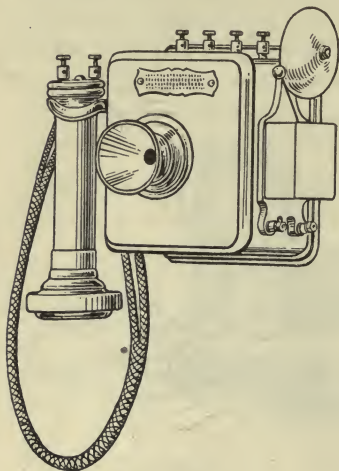


FIG. 118.

c. With the receiver off the hook, trace the local circuit through the transmitter and the primary coil, and the line circuit through the secondary coil and the receiver.

What connections are broken and what made by the lever when the receiver is removed from the hook?

d. Study and use the line till you understand its operation.

Draw one or more diagrams of the telephone, showing the various circuits and connections that you have found. Describe the telephone and its action, referring to your diagrams.

EXERCISE 76. ELECTROLYSIS AND THE STORAGE CELL

References. — Adams, 533-538; Coleman, 511-513; Car. & C., 445-447, 449-451; Ches. G. & T., 395-395 *a*; Hoad. Br., 365-370; Hoad. El., 415-420; Mumper, 269-271; Jackson, 56-67, 370-387; Mil. & G., 387-393; Went. & H., 306-307, 309-312.

Experiment 146. — *To study the effect of passing an electric current through solutions of zinc sulphate and copper sulphate, between copper and other electrodes.*

Apparatus.—Two dry or chromic acid cells ; tumbler of zinc sulphate in solution (colorless) ; tumbler of copper sulphate in solution (blue) ; copper wires, No. 16 or larger, bare or bared for about 10 cm. at the ends ; piece of emery cloth or sandpaper.

Experimental Work.—*a.* Connect the cells in series, and use the bare copper wires (or wires bared for about 10 cm. at the ends) as the battery terminals. Brighten with the emery cloth the free end of the negative terminal. The free end of the positive terminal should be dull from exposure to the air. If it is bright or plated with zinc from previous use, cut this portion off or use another wire.

Hold the battery terminals some distance apart in the solution of zinc sulphate, and close the circuit. Note any immediate change in the appearance of either terminal. Remove them occasionally for better observation. Which terminal (the positive or the negative) receives a coating of zinc? What evidence do you find that copper from the other terminal has gone into solution? The electric current causes copper to replace zinc in the compound, forming copper sulphate and depositing zinc.

b. Place a brightened end of copper wire in the zinc sulphate solution without electrical connection. Is it coated with zinc? Do you infer that electrical energy is or is not necessary for this displacement of zinc by copper?

c. Place the zinc-covered terminal in the solution of copper sulphate for an instant, without electrical connections, and observe whether the coating of zinc is removed. If so, is there any evidence that a deposit of copper has taken its place? Wipe the wire with a cloth to be sure of results. Is a supply of energy from some outside source necessary for this displacement of copper from the sulphate by zinc?

d. Take for battery terminals wires whose free ends have not been used or brightened ; and, with the circuit closed, hold these ends for a minute or two in the solution of copper sulphate. Determine from the appearance of the wires which (the positive or

the negative) has received a deposit of copper and which has been partly consumed. Was the transfer of copper between the terminals in the direction of the current or in the opposite direction?

e. If you wish to plate a nickel or a dime with copper, attach it to the terminal that receives the deposit. To attach the coin, wrap the end of the wire four or five times round a lead pencil, making the turns close together, and slip the coin between them. To make the plating uniform, it will be necessary to slip the wire into a new position on the coin three or four times.

How could the current be made to remove the plating?

Experiment 147.— *To study the construction and action of a storage cell.*

Apparatus.— Tumbler containing dilute sulphuric acid (about 10% acid by volume); two lead plates, with support as in Exercise 59; two dry cells; electric bell; high-resistance galvanometer or voltmeter; piece of emery cloth or sandpaper; connecting wires; two double connectors.

Experimental Work.— *a.* Clean the lead plates with the emery cloth or scrape them with a knife, till the surfaces are bright. Place them in the tumbler of acid, using the support to keep them in position, and connect their terminals with the galvanometer (or voltmeter). If all deposits due to previous use have been removed from the plates, there will be no deflection. The tumbler of acid and the lead plates constitute a *storage cell*. In its present condition its E. M. F. is zero. (Why?)

b. Connect the storage cell in circuit with the battery of dry cells, and connect the galvanometer as a shunt to the storage cell (Fig. 119). Note the deflection (exact reading not required). After about half a minute disconnect one of the battery terminals, and note the behavior of the galvanometer. Does it indicate an E. M. F. in the storage cell? If so, note the rapidity with which the deflection decreases as the cell loses its slight charge in sending a current through the galvanometer.

c. Again close the battery circuit through the storage cell for about half a minute, and repeat the previous observations. Note the formation of bubbles on the plates during the charging. Do they gather more abundantly on the positive or the negative plate? The bubbles at the positive plate are of oxygen; those at the negative plate, of hydrogen. Raise the lead plates out of the liquid and note their color, especially the inside surface of each, when the cell is charged and also when it is discharged.

d. Repeat all these processes and observations five or six times, noting carefully the growing color of the plates when charged, the difference between the color of the plates when charged and when discharged, and the increasing time required to discharge the cell.

Repeated charging and discharging increases the quantity of reddish brown peroxide of lead (PbO_2) that can be formed on the one plate (which?), and the quantity of spongy lead that can be formed on the other. The cell thus becomes capable of receiving a greater charge.

e. Determine from the direction of the galvanometer deflection whether the plate that is positive while the cell is being charged is also the positive plate while the cell is generating a current. Does the current generated by the cell flow through it in the same direction as the charging current or in the opposite direction?

f. If a voltmeter is used, find the voltage of the cell when charged.

g. Charge the cell, and connect it with the electric bell. It should furnish current enough to ring the bell for several seconds.

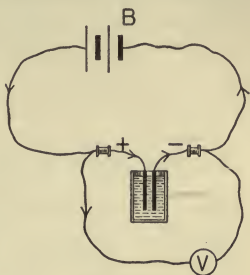


FIG. 119.

Discussion. — 1. Compare the chemical changes that take place in the zinc sulphate cell, under the action of the electric current, with those that take place in the gravity or the Daniell cell in gen-

erating a current. What transformation of energy do you infer takes place in the electrolytic cell? Give reasons.

2. What transformation of energy takes place in a storage cell while it is being charged? while it is generating a current?

3. To what extent do the facts established in this exercise lend support to the principle of the conservation of energy?

APPENDIX

TABLE I

DENSITIES IN GRAMS PER CUBIC CENTIMETER

Aluminum . . .	2.67	Alcohol (95 %) . . .	.82
Antimony, cast . . .	6.7	Blood	1.06
Beeswax	.96	Carbon disulphide . . .	1.29
Bismuth, cast . . .	9.8	Chloroform	1.5
Brass	8.4	Copper sulphate solution	1.16
Copper	8.8 to 8.9	Ether	.72
Cork	.14 to .24	Glycerine	1.27
Galena	7.58	Hydrochloric acid . . .	1.22
German silver . . .	8.5	Mercury, at 0° C. . .	13.596
Glass, crown . . .	2.5	Milk	1.03
Glass, flint	3 to 3.5	Nitric acid	1.5
Gold	19.3	Oil of turpentine . . .	.87
Ice	.917	Olive oil	.915
Iron, bar	7.8	Sulphuric acid (15 %) .	1.10
Iron, cast	7.2 to 7.3	Sulphuric acid	1.8
Ivory	1.9	Water (4° C.)	1.000
Lead	11.3 to 11.4	Water, sea	1.026
Marble	2.72		
Mercury, at 0° C. .	13.596		
Platinum	21.5		
Quartz	2.65		
Silver	10.4 to 10.5		
Steel	7.8 to 7.9		
Sulphur, native . .	2.03		
Tin	7.3		
Zinc, cast	6.86		

GASES AT 0° C. AND 76 CM. PRESSURE

Air	.001293
Carbon dioxide . . .	.001977
Hydrogen	.0000896
Nitrogen	.001256
Oxygen	.001430

TABLE II
DENSITY OF WATER AT VARIOUS TEMPERATURES

TEMPERATURE	DENSITY	TEMPERATURE	DENSITY
0° . .	.99987	16° . .	.99900
4° . .	1.00000	20° . .	.99826
8° . .	.99989	50° . .	.9882
12° . .	.99955	100° . .	.9586

TABLE III
RELATIVE CONDUCTIVITIES FOR HEAT
(Silver taken as the standard of comparison = 100.)

Silver	100	Bismuth	2
Copper	74	Ice	0.2
Brass	27	Marble	0.15
Zinc	20	Water	0.14
Tin	15	Glass	0.05
Iron	12	Wood	0.01
Lead	8.5	Air	0.007

TABLE IV
COEFFICIENTS OF LINEAR EXPANSION

Aluminum	.000023	Iron and steel	.000012
Brass	.0000188	Lead	.000028
Copper	.0000172	Platinum	.0000088
Glass	.0000085	Silver	.000019
Gold	.0000144	Hard wood	.000006

TABLE V
COEFFICIENT OF CUBICAL EXPANSION

Acetic acid	.00105	Olive oil	.0008
Alcohol (5° to 6°)	.00105	Petroleum	.0009
Alcohol (49° to 50°)	.00122	Turpentine	.0007
Ether	.0015	Water (5° to 6°)	.000022
Glycerine	.0005	Water (49° to 50°)	.00046
Mercury	.00018	Water (99° to 100°)	.00076

TABLE VI

MELTING POINTS

Aluminum . . .	657° C.	Lead . . .	327° C.
Beeswax . . .	62	Mercury . . .	- 39
Butter . . .	33	Paraffine . . .	45 to 50
Copper . . .	1084	Platinum . . .	1775
Glass . . .	1000 to 1400	Rose's fusible metal . . .	94
Gold . . .	1064	Solder, soft . . .	225
Ice . . .	0	Sulphur . . .	115
Iridium . . .	1950	Tin . . .	230
Iron, cast . . .	1100 to 1200	Wax, white . . .	65

TABLE VII

BOILING POINT

Acetic acid . . .	117° C.	Water . . .	100° C.
Alcohol, ethyl . . .	78.4	Air . . .	- 191
Alcohol, methyl . . .	66	Ammonia . . .	- 39
Ether . . .	34.9	Carbon dioxide . . .	- 78
Mercury . . .	357	Hydrogen . . .	- 238.5
Sulphur . . .	447	Nitrogen . . .	- 194.5
Sulphuric acid . . .	325	Oxygen . . .	- 182

TABLE VIII

SPECIFIC HEATS

Alcohol (0° to 50°) . . .	.615	Iron . . .	.114
Aluminum (15° to 97°) . . .	.21	Lead . . .	.031
Brass . . .	.094	Marble . . .	.21
Copper . . .	.095	Mercury . . .	.033
Ether . . .	.52	Silver . . .	.056
Glycerine . . .	.55	Steel . . .	.118
Glass . . .	.19	Turpentine . . .	.426
Ice . . .	.504	Zinc . . .	.094

TABLE IX

HEATS OF FUSION

	CALORIES		CALORIES
Ice	79.25	Silver	21.07
Iron	23 to 30	Sulphur	9.37
Lead	5.37	Tin	14.25
Mercury	2.83	Zinc	28.13

TABLE X

HEATS OF VAPORIZATION

	CALORIES		CALORIES
Alcohol	208	Sulphur	362
Ether	90	Turpentine	74
Mercury	62	Water	536

TABLE XI

VELOCITY OF SOUND IN METERS PER SECOND

Brass	3394	GASES AT 0°			
Glass	4965 to 5564	Air			332
Granite	1664	Carbon dioxide			261
Iron	5016 to 5127	Hydrogen			1269
Lead	1319 to 1368	Oxygen			317
Oak	3287 to 3991				
Steel	4768 to 5016				

TABLE XII

INDICES OF REFRACTION

Air	1.000294	Ice	1.31
Alcohol	1.36	Iceland spar, ordinary ray .	1.65
Canada balsam	1.54	Iceland spar, extraordinary	
Carbon bisulphide	1.68	ray	1.48
Diamond	2.47 to 2.75	Water	1.336
Ether	1.36	The eye :	
Glass, crown	1.53 to 1.56	Aqueous humor	1.337
Glass, flint	1.58 to 1.64	Vitreous humor	1.339
Glycerine	1.47	Crystalline lens	1.384

TABLE XIII
ELECTRIC RESISTANCE

(Ohms to 1 m. length and 1 sq. mm. cross section.)

Aluminum, annealed	.0289	Lead	.196
Copper, annealed	.0157	Manganin.	.475
Copper, hard	.0150	Mercury	.943
German silver	.2076	Platinum	.0898
Iron, pure	.0964	Silver, annealed	.0149
Iron, telegraph wire	.15	Carbon, graphite	24 to 420

TABLE XIV
ELECTROMOTIVE FORCE OF CELLS

These are only approximate values. The E.M.F. of cells varies considerably with the condition of the plates and the liquid.

	VOLTS		VOLTS
Bunsen	1.9	Grenet	2
Daniell	1.07	Grove	1.9
Edison-Lalande	.7	Leclanché	1.4
Gravity	1		

TABLE XV
TANGENTS OF ANGLES

To find the tangent of an angle not measured by a whole number of degrees, find first the tangent of the integral part of the number, and add to this the product obtained by multiplying the difference between this tangent and the tangent of the next whole number of degrees by the decimal part of the angle. For example, to find the tangent of $38^{\circ}.7$, proceed thus:—

$$\tan 38^{\circ} = .781, \tan 39^{\circ} = .810.$$

$$.810 - .781 = .029,$$

$$.7 \times .029 = .020.$$

$$\tan 38^{\circ}.7 = .781 + .020 = .801.$$

ANGLE	TANGENT	ANGLE	TANGENT	ANGLE	TANGENT	ANGLE	TANGENT
0°	.0000	23°	.424	46°	1.036	69°	2.61
1	.0175	24	.445	47	1.072	70	2.75
2	.0349	25	.466	48	1.111	71	2.90
3	.0524	26	.488	49	1.150	72	3.08
4	.0699	27	.510	50	1.192	73	3.27
5	.0875	28	.532	51	1.235	74	3.49
6	.1051	29	.554	52	1.280	75	3.73
7	.1228	30	.577	53	1.327	76	4.01
8	.1405	31	.601	54	1.376	77	4.33
9	.1584	32	.625	55	1.428	78	4.70
10	.1763	33	.649	56	1.483	79	5.14
11	.194	34	.675	57	1.540	80	5.67
12	.213	35	.700	58	1.600	81	6.31
13	.231	36	.727	59	1.664	82	7.12
14	.249	37	.754	60	1.732	83	8.14
15	.268	38	.781	61	1.804	84	9.51
16	.287	39	.810	62	1.88	85	11.43
17	.306	40	.839	63	1.96	86	14.30
18	.325	41	.869	64	2.05	87	19.08
19	.344	42	.900	65	2.14	88	28.64
20	.364	43	.933	66	2.25	89	57.29
21	.384	44	.966	67	2.36	90	∞
22	.404	45	1.000	68	2.48		

TABLE XVI

EQUIVALENTS

1 cm.	= 0.3937 in.	1 in.	= 2.54 cm.
1 km.	= 0.6214 mi.	1 m.	= 1.609 km.
1 sq. cm.	= 0.1550 sq. in.	1 sq. in.	= 6.452 sq. cm.
1 c. cm.	= 0.0610 cu. in.	1 cu. in.	= 16.387 ccm.
1 kg.	= 2.20 lb. avoird.	1 oz. avoird.	= 28.35 g.
1 l.	= 1.0567 qt. (liquid).	1 lb. avoird.	= 453.6 g.
1 l.	= 0.908 qt. (dry).		

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